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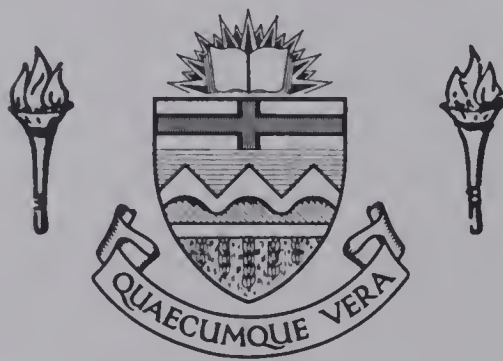
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TWO-PULSE DIFFERENCE THRESHOLDS  
AND THEIR IMPLICATIONS ABOUT SENSORY PROCESSES  
WHICH LIMIT VISUAL TEMPORAL ACUITY

by

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A THESIS  
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES  
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE  
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UNIVERSITY OF ALBERTA  
FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Two-pulse difference thresholds and their implications about sensory processes that limit visual temporal acuity", submitted by Thomy Henning Nilsson in partial fulfillment of the requirements for the degree of Master of Science, with distinction.



## ABSTRACT

This study presents the first data on visual two-pulse difference thresholds for stimuli shorter than 100 msec. These difference thresholds were studied because it was thought that such data might indicate the temporal response characteristics of the visual system.

Electronic and optical apparatus are described which permitted these thresholds to be measured using a three position, temporal forced-choice technique.

Experiment I studied two-pulse difference thresholds for pulse intervals ranging from 0 to 75 msec. A balanced factorial design was used so that each pulse interval was compared with every other interval. Stimulus luminance was varied from 50 to 2000 mL. Stimulus luminance was found to have no significant effect on the performance of the observers. This agrees with previous data on two-pulse resolution thresholds. The difference thresholds appeared to decrease monotonically as pulse interval was increased. However, a further analysis suggested that the increasing and decreasing difference thresholds might be different functions. Therefore a second experiment was proposed to investigate this possibility.

Experiment II studied increment and decrement thresholds separately for two-pulse intervals ranging from 0 to 90 msec with a stimulus luminance of 500 mL. It was found that the increment and decrement thresholds did appear to differ. Increment thresholds were a U shaped function of pulse interval with a minimum at 30 msec. However, the exact nature of the decrement threshold function was not revealed by the data.



A model is described which is based on the variation in the transmission rates of neurons and synapses in the visual pathway. This model suggests that temporal discrimination is limited by this variation since it distributes over time the afferent impulses arriving at the cortex. This model successfully predicts that the temporal difference thresholds are a U shaped function of pulse interval and that the increment and decrement thresholds might differ. Additional sensory and physiological data are discussed which seem to support the implications of the model.



## ACKNOWLEDGEMENTS

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Mitchell Kietzman introduced me to the problem of two-pulse thresholds. From him I learned the experimental techniques, and thanks to his critical commentary I saw the possibility that increment and decrement thresholds may differ.

Dr. Howarth has not only served on my committee but, beyond the call of duty, participated as an observer.

Dr. Walley took particular interest in its theoretical aspect at the onset and encouraged me to develop this further.

Fred Bleck suggested how cortical rhythms might interact with the model, and he served as an observer.

I might still be fumbling around with various scanning hypotheses if I had not read Dr. Bartley's early studies on the electrical activity in the visual system. Dr. Bartley's work led me to realize that temporal discrimination was probably being limited by the response characteristics of the optic pathway before any central scanning process could take effect.

I am particularly grateful to my fellow students who volunteered their time and effort to serve as observers. Though the data of several of these persons has not been reported since it was used to pursue earlier scanning hypotheses, their contribution is none the less, for their data pointed out the in-





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To Gillray Kandel  
and Mitchell Kietzman,  
from whom I learned psychology  
as a science and a profession



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## Introduction

### The Concept of Temporal Acuity

Visual perception of the environment extends across two dimensional parameters: time and space. Physical scientists might argue that time is merely an additional spatial dimension, but a behavioral scientist recognizes that time is effectively quite distinct from the spatial dimensions. With regards to perception this distinction can be understood when one considers the effects of spatially and temporally distributed stimuli.

The effect of spatially distributed stimuli is an immediately perceivable phenomenon, and spatial discrimination seems to depend primarily on the anatomical interrelations of receptors in the visual system. This is not the situation with temporally distributed stimuli. Temporally successive stimuli produce transient activity in the visual system; and, because of this, immediate effects of an initial stimulus are no longer present when a subsequent stimulus occurs. As a result temporal discrimination depends primarily on the course of events or processes which stimuli activate in the visual system.

It is an interest in these sensory processes which has led the author to the study of the ability to make temporal discriminations.

The ability of a sensory system to discriminate a difference in the distribution of stimuli detectable by that system can be defined as its acuity. As an example, the use of the Landolt "C" involves asking the observer to report the position of the interruption in an otherwise continuous circle. While questions of spatial acuity have been widely dealt with in both



research and applied fields of endeavor, the concept of temporal acuity is just beginning to be recognized.

Geldard (1936, 1953) has pointed out that temporal acuity is analogous to spatial acuity. Just as the Landolt "C" involves discriminating the interruption of a small spatial interval between the open ends of the "C", one could similarly ask an observer to discriminate an interruption between two stimuli separated by a small interval of time.

Pieron (1952, p. 42), states that, "temporal acuity corresponds to the discriminative power in the time dimension, just as spatial acuities represent discriminative power in the dimension of space." Pieron further suggests that temporal acuity could be defined as the minimum interval between two events which is necessary in order to perceive their successiveness and order of appearance.

However, judgements of temporal successiveness and order do not necessarily correspond to the actual order of two events. Under some conditions, for example, the second event may be perceived as occurring before the first event. Therefore temporal acuity may be more generally defined as any discriminable difference which is produced by varying only the temporal distribution of two events. This definition ties temporal acuity to the temporal parameter of the stimuli alone, and it permits the observer to make a discrimination on the basis of any subjective effect which this temporal variation produces.<sup>1</sup>

This definition leads to two types of temporal acuity thresholds: 1) "absolute or resolution thresholds" which would refer to the minimum interval between two successive stimuli



which are discriminable as different from two simultaneous stimuli; 2) "difference thresholds" which would refer to the discriminable difference in intervals between two stimuli. It will be argued that the difference thresholds are important in understanding the sensory processes which mediate temporal discriminations, even though the resolution threshold is most similar to Pieron's definition of temporal acuity.

### Resolution Measures of Temporal Acuity

One of the earliest studies of the limits of human ability to temporally resolve two visual events was reported by Dunlap (1915). Using two geared episcotisters driven by a synchronous motor, Dunlap binocularly presented stimuli which consisted of two successive pulses whose interval could be varied. The observer was asked to discriminate these two-pulse stimuli from stimuli consisting of two similar pulses which were also successive but not separated. A method of constant stimuli was used. With pulse durations of 10 msec, this discrimination could be made when the pulse interval was about 50 msec. Changes in intensity from 3 to 168 meter-candles did not appreciably change the minimal length of the pulse interval which produced discrimination. However, increasing the duration of the pulses decreased this minimal discernable pulse interval.

Mahneke (1958) repeated Dunlap's experiment using improved electronic instrumentation, observing stimuli monocularly through an artificial pupil, and extending the range of durations observed. Mahneke, however, did not vary intensity, but





other than this their findings agree. Mahneke found that as pulse duration increased from 1 to 300 msec, the minimal discernable dark interval decreased from 60 to 3 msec. Transformation of this data indicated that the duration of this dark interval was a nearly linear function of the log of pulse duration. This led Mahneke to conclude that the total energy produced by increasing pulse duration was improving temporal discrimination of intermittent stimuli in accordance with the Ferry-Porter law. But if temporal discrimination was improved by increasing stimulus energy, then Dunlap (1915) should have found this effect when he increased stimulus intensity, but he did not.

The Ferry-Porter law states the common observation that CFF increases with an increase in stimulus intensity. In view of this, Dunlap's finding that increasing intensity did not reduce the minimal discernable dark interval is perhaps surprising. An experiment by Bartley, Nelson, and Ranney (1961) further demonstrates the lack of an intensity effect reported by Dunlap and simultaneously casts doubt on Mahneke's explanation of the pulse duration effect. Bartley, Nelson, and Ranney varied both the length and intensity of a train of intermittent stimulation. They found that varying intensity did not change CFF when the train length was reduced below five pulses.

These earlier studies determined the thresholds of temporal discrimination simply in a qualitative fashion. They had the observers report whether they perceived the stimuli as one or two light flashes. The problem with this approach is





its dependence on the observer's criteria regarding "twoness". Other studies have tried to get around this problem by using more sophisticated psychophysical procedures. These have yielded more quantitative measures which are probably closer to the sensory processes involved in these discriminations.

Lewis (1967) used a forced-choice technique to determine two-pulse thresholds. On a given trial, two stimuli were presented separated by one second. One stimulus, the comparison stimulus, consisted of two 1 msec light pulses separated by 1 msec. The other stimulus, the test stimulus, consisted of two 1 msec pulses separated by an interval which was systematically varied. The observer was asked to judge which stimulus appeared to be longer. The stimuli were presented first or second at random. Discrimination thresholds were determined at various luminance levels ranging from .3 to 1000 mL.

Lewis found that the two pulse threshold decreased from about 33 msec at .3mL to between 20 and 25 msec at 10 mL. Further increases in luminance produced little change in threshold.

Kietzman (1967) used a three stimulus forced-choice technique which seems to yield an even more objective measure of two-pulse resolution thresholds. He presented two comparison stimuli rather than one. The pulses were of two msec duration, and the interval of the test stimulus was randomly varied. Other than this, the procedure was essentially the same as Lewis\*. However, rather than asking the observers to report which stimulus was longer, Kietzman asked them to report merely which stimulus was different from the other two. In this manner the



data was independent of the observers' criteria regarding some given stimulus parameter such as apparent duration, and the observers would be set to make a discrimination on any perceptible difference produced by the test stimulus.

In Kietzman's study various observers correctly discriminated the test stimulus 50% of the time (corrected for chance) when its pulse interval was between 10 and 33 msec. There was no systematic change in threshold as stimulus luminance was varied from 2.5 to 612 mL.

While Lewis' (1967) and Kietzman's (1967) experiments yielded more sensitive measures of the threshold of two-pulse resolution, their data agree with Dunlap's (1915) with regards to the effects of intensity on this threshold. Apparently as long as the luminance is above some minimal value of about 1 mL for pulse durations of 1 msec, increases in luminance will have little or no effect on the two-pulse resolution thresholds.

Lewis' finding that the threshold did increase at still lower luminance levels is not surprising when one calculates the brightness of two msec of stimulation at 1 mL according to Bloch's law. Taking Bartlett's (1965) value of the critical duration as 100 msec, the effectiveness of such stimuli are seen to be equivalent to .02 mL of steady illumination. According to Riggs (1965) this would be below the photopic threshold. Presumably different processes would be involved in the detection of such scotopic stimuli.

Further experiments by Kietzman and Sutton (1967) studied other stimulus parameters influencing two-pulse thresholds.



In one of their experiments they tested whether the actual interval between the pulses of the test stimulus or the total duration of the test stimulus mediated temporal discrimination. Two types of test stimuli were used: one type consisted of a pair of 2 msec pulses separated by some interval, the other type was a single, equal energy pulse whose duration was varied to the same extent as the period of the two pulse stimulus. The comparison stimuli consisted of single 4 msec pulses of equal energy. A forced-choice procedure similar to that of Kietzman (1967) was used.

Kietzman and Sutton's data indicated that there was no difference in the discrimination thresholds of these two types of test stimuli. A two-pulse stimulus with a dark interval had the same threshold as a single pulse stimulus whose duration equalled the total duration of the two-pulse stimulus. This indicates that the two-pulse discriminations are made on the basis of their total duration and not on the duration of the dark interval.

In another experiment Kietzman and Sutton sought to test whether the difference in duration between the test and comparison stimuli was a factor in temporal discrimination. Using a procedure similar to the above, this time they varied the total duration of comparison stimulus pulses so that comparison stimulus duration equalled the total duration of a two pulse test stimulus whose pulse interval was varied. All stimuli were equated for energy by adjusting intensity. The data showed that discrimination was considerably poorer when





the comparison stimuli were equated for duration. This indicated that the difference between test and comparison stimuli durations is also a factor.

Kietzman and Sutton also raised a question about what is actually being measured in forced-choice experiments on temporal resolution. They attempted to study the cues used by their observers to make these discriminations. After each choice the observers reported the cues which had influenced their decision as to which stimulus was different. It was noted whether the use of each cue had led to a successful discrimination on each trial. Kietzman and Sutton found that a variety of cues could be successfully used by observers. These cues differed with the stimulus conditions, and different cues were used by different observers.

This procedure of obtaining phenomenal reports may be questionable. Blackwell (1952) has pointed out that a forced-choice technique produces more sensitive threshold measures because it tends to maximize the utilization of all available sensory cues. The combined effect of such cues may be difficult for an observer to describe. One may even be dealing with sensory cues which can not be specified in ordinary perceptual terms.

A two-pulse experiment by Bartlett and White (1965) seems to bear this out. They asked observers to discriminate three pairs of light pulses which had pulse intervals of 9, 16, and 25 msec. Though observers reported that there was no difference in the perceived brightness of these stimuli, a





forced-choice technique revealed a significant discrimination bias towards stimuli with a 9 msec interval. Furthermore, averaged evoked potentials for the 9 and 16 msec interval stimuli revealed differences in amplitude and waveform.

These considerations suggest that instead of trying to relate temporal resolution to particular attributes of the stimuli such as flicker or brightness, we might simply recognize that these discriminations are based on differential physiological effects evoked by differences in the temporal distribution of energy in the stimuli. Since the sensory-correlates of these effects can not be quantitatively defined, it would be better to permit the observer to use all subjective effects for discrimination, and then try to relate this discrimination to the differential effects which were produced by temporal variation. This procedure implies that temporal acuity be defined as was suggested on page 2.

### Significance of Temporal Difference Thresholds

While several studies have measured temporal resolution thresholds, no previous experiments have systematically studied the difference thresholds of temporal acuity. There are good reasons for doing so.

To begin with, resolution thresholds which have been measured by a forced-choice technique are always difference thresholds of sorts. In a forced-choice technique the observer compares the effects of one stimulus with those of another and makes his choice on the basis of a difference between their effects. Since both stimuli contribute to this difference,



little can be learned about the basis of these discriminations by varying just one stimulus. Therefore both types of forced-choice stimuli must be systematically varied to determine how the discriminable difference between their effects relates to the stimuli themselves. In effect this procedure is that of measuring the difference thresholds.

Woodworth and Schlosberg (1954, p. 220) point out that the central effectiveness of a stimulus depends not only on the stimulus itself but also on, "the sensitivity of the receptor, the efficiency of the conducting path, and the background level of activity of the center. If the central effect on a given trial is greater than a certain minimum, the center will discharge, yielding a response; i.e., 'I hear it.' The stimulus which produces this minimum effect is the stimulus threshold on that trial. But the complex of factors listed above will vary from trial to trial, yielding a more-or-less normal distribution of momentary T's (thresholds)."

During the measurement of a difference threshold, however, the organism is comparing the effects of a test stimulus relative not only to a more-or-less normal variability of its system, but also to the effects produced by the comparison stimuli. While these stimulus effects may vary normally, the discriminable difference between these effects may not necessarily vary normally, since the effectiveness of this difference is determined entirely by processes within the center. Therefore, to the extent that they do not show normal variance, difference thresholds can yield information on the central processes which mediate discrimination.



The primary reason why temporal difference thresholds were studied in the present experiment was to determine if these thresholds showed evidence of other than normal variance in the sensory processes which mediate their discrimination.





## PURPOSE

Previous studies (Dunlap, 1915; Kietzman, 1967; Lewis, 1967; Mahneke, 1958; and several others making related measures) have found that two identical, brief, successive, visual events can be resolved if separated by an interval of about 25 msec. These studies also indicated that this threshold of temporal resolution is not dependent on the brightness of the stimuli providing that they fall within the photopic range. Even though intensity may not be an important variable, stimulus duration is. Two studies (Kietzman, 1967; Mahneke, 1958) indicate that these discriminations may be made primarily on the basis of differences in the total duration of two-pulse stimuli.

Blackwell (1952) points out that among present psychophysical methods the forced choice technique provides the most sensitive and reliable measure of visual thresholds. This seems to be borne out in experiments by Bartlett and White (1965), Kietzman (1967), and Lewis (1967) measuring temporal resolution thresholds. However a study by Kietzman and Sutton (1967) indicates that there is still some question as to what is being measured by this technique.

No previous study has investigated the difference thresholds of temporal acuity or whether these thresholds might be dependent on stimulus brightness. Yet previous studies do indicate that the difference in stimulus duration is an important factor in these acuity discriminations. Furthermore, as has just been argued, the use of a forced-choice technique demands that difference thresholds be measured if complete information is to be gained about what is being measured.





Specifically this study attempted to measure difference thresholds of temporal acuity at various luminance levels. A forced-choice technique was used so that these measures might give the closest indication of the sensory processes involved in temporal acuity discriminations.



## METHOD

A forced-choice method can be used with either a spatial or temporal separation of the stimuli to be discriminated. Stimulating different areas of the retina simultaneously was judged undesirable in the present experiment due to: 1) the difficulty of attending simultaneously to several stimuli of short duration; 2) the difference in temporal acuity of different portions of the retina, reported by Hylkema (1942); 3) the variation in intensity of and sensitivity to light directed towards different portions of the retina, reported by Stiles and Crawford (1933); and 4) the possibility of retinal interaction occurring between simultaneous stimuli. Stimulating the same area of the retina successively avoids these problems as long as there is sufficient time between stimuli to eliminate temporal interaction. Crawford (1947) found no further changes in threshold of a test stimulus when it occurred one second after a conditioning stimulus. This suggests that there should be negligible interaction between successive stimuli as long as the time between stimulus positions is at least one second.

A forced-choice method can also be accomplished with one, two, three, or more stimuli to be discriminated. Kietzman and Sutton (1967) reported that a variety of cues are used by observers in making these discriminations. Therefore it would be difficult to use a one or two position technique, which requires the observer to discriminate some particular aspect of the stimuli. With a three position technique, two stimuli can always be the same and one stimulus different. The observer then does not have to be instructed as to what cues to use. He merely



reports which position contained the different stimulus. This allows the observer to use any and all possible cues to make a discrimination.

Obviously more than three positions could also be used to this advantage as long as only one position was different. Four positions would reduce the chance level of accuracy from 33% to 25%, but four positions would also require 33% more observing time. The  $1/4$  reduction in chance level achieved by a four position technique would be undesirable since  $1/3$  more replications with a three position technique would provide more information in the same amount of time. More important than simple gain considerations, previous experience has shown the author that observers have considerable difficulty in keeping track of four stimuli in a four position procedure. The very nature of temporal position demands the use of memory to make a discrimination. Since memory is not being investigated, it would seem desirable to keep this factor to a minimum.

Because of the above considerations, a three position, temporal forced-choice method was used to measure the j.n.d. thresholds of temporal resolution. This method is similar to that used by Kietzman (1967) and agrees with the recommendations made by Blackwell (1952) for measuring visual thresholds.

The findings of Kietzman and Sutton (1967) show that temporal discrimination thresholds depend primarily on the durations of the stimuli. Their data showed essentially the same effects when stimulus duration was varied either by varying the interval between a pair of light pulses or by varying the dur-





ation of a single pulse and adjusting its intensity to maintain equal energy. The problem with varying the duration of single pulses is precisely how to adjust their intensity to maintain equal energy for stimuli of different durations. This problem requires a complicated solution which involves either: 1) a light source whose intensity can be varied without changing any of its other characteristics, 2) motor driven neutral density wedges, or 3) a multiple channel optical system. Varying the interval between two pulses presents no such problems. Also asking the observer to discriminate successive visual events, rather than changes in duration, seems a more direct approach to the problem of temporal acuity.

For these reasons the j.n.d. thresholds of temporal resolution were measured with stimuli composed of two brief light pulses separated by a varied interval. This method is similar to that used by Bartlett and White (1965), Dunlap (1915), Kietzman (1967), and Mahneke (1958).





## APPARATUS

Light Source

A primary requirement for studying temporal acuity under threshold conditions is a light source which can accurately be turned on and off for durations and intervals ranging from near 0 to 100 msec. Reliability of duration and intensity of the light pulses demands that this source have rapid rise and decay times with a consistent intensity for the duration of its "on" time. The light source should emit a fairly uniform, broad band spectrum in the visible region at intensities sufficient to permit considerable variation in luminance levels above threshold.

These requirements were met by a concentrated arc lamp known as a glow modulator tube. This source produces a very intense point of light, roughly 2 mm in diameter, when a D.C. current of sufficient voltage is passed through the lamp. The use of this light source for visual research has been described previously (Buchman-Olsen and Rosenflach, 1957; Engel and Howat, 1966; Matin, 1964; Riggs, 1965). It was used in two-pulse threshold experiments by Kietzman (1967), Kietzman and Sutton (1967), and Mahneke (1958). However, data on the spectral output of these sources when pulsed for durations of less than 100 msec is not commonly known.

Tests were made of the light output of glow modulators under various operating conditions. Information was sought about the effects that operating current, "on" duration, and cycling time had on the spectral response of this light source.



A description of these glow modulator tests and the obtained results are presented in the Appendix. The tests indicated that the glow modulator has high spectral stability. Over a wide range of rates and durations of intermittent operation, the average change in light output across all wave lengths was less than 5%.

The present experiment used a Sylvania R1131C glow modulator light source. The source was run at 36 ma supplied by a constant voltage power supply. An electronic gate enabled the power to the lamp to be controlled by weak electronic signals. To improve the stability of its rise time, the glow modulator was irradiated by an Ultraviolet Products UVS-11 ultraviolet lamp. (Matin, 1964) This relatively high intensity ultraviolet source reduced the rise time of the glow modulator to less than 10 usec. The decay time of the glow modulator was less than 50 usec for pulses of 2 msec duration. A Kodak Wratten K2 filter was placed in front of the glow modulator housing to eliminate any stray ultraviolet or violet radiation in the stimulus field. The full illuminance of the light source was 24000 ft-candles as measured by a MacBeth illuminometer at the position of the pupil in the optical system. Kodak Wratten neutral density filters were added to control intensity by reducing the luminance of the stimulus.

### Timers

Equally important for the study of these phenomena were pulse generators to accurately control the light source. This meant generating electronic signals for precise durations rang-



ing from 0 to 100 msec to produce the double pulse stimuli. The use of the three position temporal forced-choice method called for additional pulse generators to produce longer delay intervals between stimulus positions. In order to rapidly change the temporal position of the test stimulus after every trial, a means for programing these timers was deemed desirable. A timer circuit was sought which would fulfill these requirements and still be relatively simple to build and low in cost.

Humblet (1964) presented a circuit which seemed a good approach to these requirements. In particular the use of a recently developed unijunction transistor to switch a monostable multivibrator offered a great range of pulse durations together with good stability. Pulse duration was determined by the decay time of the unijunction's biasing capacitor which discharged through a resistor. By using several sizes of capacitors and varying resistance one could regulate the pulse duration of this circuit. Humblet's circuit was modified in the following manner. A linear multiturn potentiometer was substituted for the timing resistor. The setting of this potentiometer was indicated by a dial with digital readout. Provision for switching high stability mylar capacitors was incorporated to cover various ranges of duration. The operating condition of the circuit was displayed by two indicator lamps driven by the transistors in the multivibrator. Provision was made for both manual start and triggering by other timers. The modified circuit is shown in Figure 1.

The modified circuit was thoroughly tested to determine its stability in generating pulses with durations ranging from .01 to





20,000 msec. Stability of the power supply was found to be a critical factor. During the tests and in subsequent use, the timers were powered by a Harrison Labs regulated power supply. Duration of the timer pulses was measured by a TSI Aptimeter digital clock. Moment to moment variability in the duration of the timer was less than .1%. Week to week variability was less than 1% over the full range of durations. The new timer was considered very adequate for the task at hand.

Eight identical timers of this design were built. This similarity of units permitted complete interchangeability of their functions. Each timer was calibrated for its particular timing function by using a Techtronics 503 oscilloscope. A switching module was added which enabled rapid changing of the sequence in which the timers operated. A diagram of the electronic apparatus is shown in Figure 2. These timers performed satisfactorily for the duration of the experiment and have proved to be dependable in several subsequent experiments.

### Optical System

The stimuli were presented by means of a two channel Maxwellian view optical system shown in Figure 3. The use of such an optical system in visual research has been fully described by Boynton (1966) and Westheimer (1966). One channel was for the light stimuli themselves. This channel contained the glow modulator light source, a 5 cm fl collimating lens, Kodak Wratten neutral density filters, a field stop, a 30 cm fl achromatic viewing lens, and a 4 mm exit pupil. A second channel provided the fixation. This channel contained a high





intensity filament lamp, a 5 cm fl collimating lens, a Kodak Wratten 89B filter, a field stop, and a cover glass centered at  $45^{\circ}$  in the first channel between its field stop and viewing lens. All optical components were mounted in carriages on triangular optical benches. Black velvet cloth surrounded the two channels to prevent any detectable stray light in the system. The optical benches were set on a rigid optical table of tripod design. Observations were made from a light proof, sound deadened, ventilated booth. Head position was maintained by a bite-board system. The view consisted of dim, deep red, open crosshairs which were on continuously. Stimuli with a  $35^{\circ}$  visual angle were presented in the space in the center of the crosshairs.

Further details on the design of this apparatus are shown in Appendix B.



## EXPERIMENT I

Observers

A total of six observers participated in the first experiment. Five of these, including the author, were graduate students, 21 - 25 years of age, from the Department of Psychology. One observer (E.H.) was a professor in the same department. Observers M.F. and C.L. were female. The observers were informed about the purpose of the experiment and had volunteered to participate. Only T.N. was experienced at making threshold observations in a Maxwellian view system.

The observers were divided into two groups: a high intensity group which observed the stimuli at 2000 and 200 m $\mu$ L, and a low intensity group which observed the stimuli at 200 and 50 m $\mu$ L. Each observer participated for ten one hour sessions on ten fairly consecutive days.

Procedure

The j.n.d. thresholds of two pulse temporal resolution were measured by presenting stimuli consisting of two 1 msec light pulses separated by some dark interval. The duration of this interval was varied within the range of the critical duration. Using the three position temporal forced-choice method, three two-pulse stimuli were presented successively at 1 sec delay intervals. The pulse intervals within two of the stimuli were always identical. These served as comparison stimuli. The pulse interval within one of the stimuli was always different from these. The different stimulus was the test stimulus. An observer was asked to report which temporal



position--the first, second, or third--contained the stimulus which was the most different.

In order to cover the time range of the critical duration, it was necessary to select a range of double pulse intervals which would result in discriminations ranging from chance to almost 100% correct. Clearly if the range of intervals chosen was too small, the task would be too difficult for the observers, and they might never learn to respond to the difference cues. And on the other hand, if the range of intervals was too large, the task would be too easy for the observers, and they might never discriminate near threshold cues. Preliminary observations by C.L. and M.F. indicated a pulse interval range of from 0 to 75 msec might be suitable.

The procedure also had to be balanced between the amount of information which could be obtained from the data and the amount of time which an observer would spend making these observations. The preliminary sessions indicated that one hour was about the optimal period for which observers were willing to continue. It was possible to run 120 trials in a one hour session.

Six double pulse intervals of 0, 15, 30, 45, 60, and 75 msec duration were used. A completely balanced design was employed so that each interval in both comparison and test stimuli was compared with every other interval. This resulted in a  $6 \times 5$  factorial design with 30 different comparison and test interval combinations since each interval was not compared with itself. Conditions with identical comparison and test stimuli were eliminated so that 4 replications could be obtained within the allotted 120 trials per session.





To ascertain the effect of intensity, the 4 replications were divided between two intensity levels, making a  $2 \times 6 \times 5$  factorial design for each intensity group with 2 replications per session. Because each observer participated for 10 sessions, a total of 20 responses were obtained at each intensity  $\times$  comparison interval  $\times$  test interval condition per observer.

To save time in changing intensity conditions, all observations were made first at one intensity then the other within a session with luminance levels randomly ordered. In order to reduce time between trials, the same comparison interval was presented in a block of ten trials. Each test interval was presented twice within each comparison block. A computer generated table of random numbers determined the order of the comparison blocks, the order of the test intervals, and the temporal position of the test stimulus.

The observers dark adapted in the booth for the first five minutes of each experimental session. After this period of dark adaptation the experimenter signaled the observer via a buzzer to begin. The observer set himself and then pressed a button triggering the timers. One second after triggering, the first position stimulus was presented. The second and third positions followed at 1 sec intervals. Employing pre-arranged buzzer signals, the observer reported the stimulus pair he perceived to be most different. All subsequent trials followed the same format. No feedback was given the observer regarding the correctness of his responses except during a short practice session preceding the experiment proper.





After every block of ten trials the observer rested about one minute. After six blocks of trials, the observer was permitted a somewhat longer rest.

### Data

Data are presented in terms of the percentage of observations for which each observer correctly reported the temporal position of the stimulus with the different pulse interval. When interpreting these data, it should be kept in mind that with a three position forced choice method 33% correct represents only a chance level of discrimination, while 66% represents discrimination at the 50% level, when correcting for chance (Blackwell, 1952). To facilitate the interpretation of the graphs, chance level discrimination is plotted for conditions where comparison and test intervals are equal, even though these conditions were not observed. The rationale for this is that discrimination of three identical stimuli in a forced choice procedure can not be other than chance.

The data from the first experiment are presented in Tables 1 and 2. Each entry is based on 20 judgements by that observer.

The results of an analysis of variance are presented in Tables 3 and 4. Within both the high and low intensity groups, the variance due to stimulus intervals ( $F > 10.0$ , 29 & 58 d.f.,  $p < .01$ ) and to subjects ( $F > 10.0$ , 2 & 58 d.f.,  $p < .01$ ) was highly significant. Variance due to intensity was not significant in the high intensity group ( $F < 1$ , 1 & 58 d.f.,  $p > .25$ ) or the low intensity group ( $F = 3.25$ , 1 & 58 d.f.,  $p > .05$ ). Interactions between intervals and subjects ( $F < 1.5$ , 58 & 58 d.f.,  $p > .05$ ), inter-



vals and intensity ( $F = 1.5$ , 29 & 58 d.f.,  $p > .05$ ), and subjects and intensity ( $F = 1$ , 2 & 58 d.f.,  $p > .25$ ) were not significant in either group. Comparison was made of the performance of the high and low intensity groups at 200 mL. Performances of the two groups did not differ significantly ( $F < 1$ , 1 & 4 d.f.,  $p > .25$ ). An interaction between groups and intervals was also not significant ( $F < 1$ , 29 & 114 d.f.,  $p > .25$ ). A comparison was also made of the performance of the high and low intensity groups at 2000 and 50 mL respectively. Again the variance due to intensity ( $F < 1$ , 1 & 4 d.f.,  $p > .25$ ) and the interaction between intensity and interval ( $F < 1$ , 29 & 114 d.f.,  $p > .25$ ) were not significant.

Figure 4 shows the data for the 0 - 75 msec range averaged across all subjects and intensities. Each data point is based on a total of 480 judgements made by six observers at three intensity levels. Percent correct discrimination is plotted as a function of test stimulus interval for the various comparison intervals. In general Figure 4 shows that: 1. Discrimination of time interval differences between pulse pairs increases as test interval increases with short comparison intervals. 2. Discrimination decreases as test interval increases with long comparison intervals. 3. Discrimination decreases as test interval increases to the value of the comparison interval with intermediate comparison intervals, and then increases as test interval increases beyond that value. The averaged discrimination of the groups never rose above 90% correct, although a few observers achieved 100% correct discrimination when comparison and test intervals differed greatly.



Figure 5 shows the 66% j.n.d. thresholds plotted as a function of comparison interval. These thresholds were obtained by determining for each comparison interval what test interval would, according to Figure 4, be discriminable 66% of the time. The absolute value of the difference between comparison interval and discriminable test interval was taken as the j.n.d. threshold. Figure 5 indicates that the j.n.d. threshold of two pulse discrimination decreases nearly linearly as the comparison interval increases.

In order to do a trend analysis on the j.n.d. thresholds, the j.n.d. thresholds for individual observers were obtained from graphs of their performance at each intensity level. Table 5 shows this data. Each entry is based on a total of 100 judgements. In cases where an observer showed above threshold discrimination at two test intervals (one shorter and one longer than the comparison interval) the difference threshold was obtained by averaging the absolute values of the two difference thresholds. All observers showed a decrease in temporal difference threshold as comparison interval was increased. However, not all observers showed above threshold discrimination for all comparison intervals; the data of these latter observers were not included in this analysis.

Table 5 shows the results of an analysis of variance and a trend analysis of the data for those observers who showed above threshold discrimination at all comparison intervals. The analysis of variance indicates that these selected observers did not differ significantly in their j.n.d. thresholds ( $F = 2, 6 \text{ \& } 30$  d.f.,  $p > .10$ ). Variance due to comparison intervals was significant ( $F > 10, 5 \text{ \& } 30$  d.f.,  $p < .01$ ).





The trend analysis indicates that the decrease in j.n.d. threshold with increase in comparison interval is significantly linear ( $F > 10$ , 1 & 30 d.f.,  $p < .01$ ). Deviation from this linearity is also significant ( $F = 8.4$ , 4 & 30 d.f.,  $p < .01$ ), but the quadratic ( $F = 3.6$ , 1 & 30 d.f.,  $p > .05$ ) and the cubic trends ( $F = 3.6$ , 1 & 30 d.f.,  $p < .05$ ) are not significant.

The average j.n.d. thresholds for these selected observers are shown in Figure 6 as a function of comparison interval. Each point is based on a total of 700 judgements made by four observers at three luminance levels. Reflecting the selection of these observers, the j.n.d. thresholds are seen to decrease more with increase in comparison interval than they do in Figure 5, which is based on all observers

### Discussion

The j.n.d. threshold observations in experiment I were made by two groups of observers who viewed two pulse stimuli at three intensity levels. The high intensity group viewed stimuli at 2000 and 200 m $\mu$ L; the low intensity group viewed stimuli at 200 and 50 m $\mu$ L. Each stimulus was composed of two 1 msec light pulses, for a total light duration of 2 msec. On a sensory level, when correction is made for Bloch's law, the stimuli used in this study vary in effectiveness from near scotopic threshold to daylight levels of brightness (Riggs, 1965).

Analysis of the data in Tables 3 and 4 showed that: 1) Variation in intensity did not significantly affect the discrimination performance of either group of observers. 2) The two groups did not differ significantly in their performance at the





same intensity. 3) The two groups did not differ significantly at 2000 and 50 mL respectively. Since there was no evidence of any significant interactions with intensity, the lack of a significant difference in their separate performance at 2000 and 50 mL indicates that temporal discrimination does not change significantly over this entire range of intensities.

The lack of an intensity effect for stimulus luminances greater than 50 mL for durations of 2 msec augments the studies by Dunlap (1915) and Kietzman (1967) who found this to be true for the absolute threshold of temporal resolution. This finding indicates a similarity between the processes in the visual system which limit temporal resolution and the processes which mediate temporal difference discrimination.

The temporal discrimination functions in Figure 4 indicate that discrimination of a test interval improves as the difference between test and comparison intervals increases. This result is hardly surprising, but it augments the finding by Kietzman and Sutton (1967) that the difference in total duration of test and comparison stimuli is of major importance.

What is surprising is that Figures 5 and 6 indicate that the temporal difference threshold is a monotonically decreasing function of pulse interval. This is not what is usually found for most measures of perceptual difference thresholds; rather it shows a relation which is inverse to the Weber-Fechner Law.

It will be recalled that these are absolute difference thresholds with no distinction being made as to whether the discriminable test stimulus was longer or shorter than the comparison.



In this respect the measures are comparable to most psychophysical studies which calculate the j.n.d.'s as one half of the interval of uncertainty (Woodworth and Schlosberg, 1954).

The uncertainty interval concept of the j.n.d. threshold assumes that the observer is making these discriminations against some amount of background noise and random variability in the system. However, is temporal acuity in the visual system limited as much by noise as by the characteristics of the visual pathway which determine its response to various temporal distributions of light energy? The traditional concept implies that the difference thresholds are more-or-less the same whether the threshold stimulus is greater or less than the comparison stimulus. But the possibility of a different picture emerges when we look separately at the temporal difference thresholds for test stimuli which are longer and shorter than the comparison stimuli. These thresholds will be referred to as "increment" and "decrement" thresholds respectively.

To accomplish this analysis, the increment and decrement difference thresholds were obtained from graphs of each observer's performance at each intensity level. These thresholds are shown in Table 6. The averages of these thresholds at each comparison interval are plotted in Figure 7.

Figure 7 reveals that as pulse duration is increased from 0 to 45 msec the increment difference threshold decreases monotonically. Since no decrement thresholds were obtained below 45 msec, the analysis so far agrees with the data of Figures 5 and 6. But as comparison interval increases from 45 to 60 msec, the increment threshold now increases. The decrement threshold also increases somewhat between 45 and 60 msec but decreases between 60 and 75 msec.



The analysis of the temporal j.n.d. threshold data into increment and decrement thresholds suggests that temporal acuity may not simply improve as two-pulse interval is increased from 0 to 75 msec. Do these temporal discriminations also involve different threshold functions depending on whether the observer is discriminating a test stimulus which is longer or shorter than the comparison? Such a difference between the increment and decrement thresholds would imply that these discriminations may not simply be limited by random variability in the visual system but may rather involve inherent temporal response characteristics of the system.

The data described so far is obviously not sufficient to provide a definitive answer to this question. Increment and decrement thresholds would have to be measured at intervals beyond 60 msec to determine if they continue to increase and decrease respectively. An additional decrement threshold could also be measured below 45 msec to see if this decrement threshold would also differ from a comparable increment threshold.

A second experiment was therefore conducted to obtain further data on two-pulse temporal difference thresholds.







## EXPERIMENT II

Observers

Two male observers, 28 and 24 years of age, participated in the second experiment. One was a research associate, the other a research assistant in the Department of Psychology. One observer (F.B.) was highly experienced at making threshold observations of intermittent stimuli. The other observer (D.W.) was not experienced with visual experiments, and therefore he was given two preliminary practice sessions. During the first of these sessions D.W. received feedback as to the accuracy of his judgements.

Procedure

Experiment II sought to obtain increment difference thresholds for comparison stimuli with intervals of 0, 15, 30, 45, 60, 75, and 90 msec. and decrement difference thresholds with 30, 45, 60, 75, and 90 msec intervals. Because Experiment I indicated that the absolute difference threshold for the 15 msec comparison interval was greater than 30 msec, it seemed unlikely that decrement thresholds could be measured for comparison stimuli with intervals much shorter than 30 msec.

Since the data was collected over a wider range of comparison conditions than in Experiment I, the range of test intervals had to be reduced in order to prevent the experimental sessions from becoming unduly long. Some preliminary sessions with observer F.B. indicated that difference thresholds could be determined for all comparison conditions with test stimuli which differed from the comparison intervals by 7.5, 22.5, and 37.5 msec.<sup>2</sup> This



resulted in a factorial design with  $12 \times 3$  comparison - test conditions.

Four replications of each comparison - test condition were run during a session, making a total of 144 observations per session. These sessions lasted approximately 50 minutes. Reflecting the greater experience of the observers and experimenter, the sessions in the second experiment were somewhat shorter than those in the first even though more observations were made. Each observer participated for 10 experimental sessions making a total of 40 observations per comparison - test condition per observer.

A single stimulus luminance of 500 mL was used. The actual procedure during an experimental session was essentially the same as in Experiment I. However, the comparison intervals were now presented in blocks of twelve trials each, and the test intervals used with that comparison interval were presented four times each in a comparison block.

Some preliminary sessions with the author as an observer indicated that the session to session variability of the observer's judgements could be reduced by informing him whether the test stimuli were longer or shorter than the comparison. When not informed as to the direction of the difference, the observer's judgements were markedly less accurate during blocks of trials having as initial test stimuli those with the shorter difference in interval. Apparently test stimuli with longer differences from the comparison stimuli served to indicate which cues were not relevant. Therefore the observers in Experiment II were informed prior to each block of trials whether the test intervals would be longer or shorter than the comparison.



## Data

The data are given in terms of the percentage of correct discriminations of the test stimulus on a total of 40 observations of each comparison - test condition. Percent correct discrimination is plotted as a function of test interval for the various comparison intervals. To facilitate the interpretation of these graphs, chance level discrimination (33%) is plotted for conditions where comparison and test intervals are equal, even though these conditions were not observed. The rationale for this has been already presented.

Data for the second experiment are presented in Figures 8 and 9 for observers F.B. and D.W. respectively. In general, these discrimination curves appear to be similar to those of the first experiment. They indicate that percent correct discrimination decreases as the value of the test stimulus interval approaches the value of the comparison stimuli interval from either above or below.

Difference thresholds were determined from Figure 8 and 9 by noting where the discrimination curves indicated 66% correct discrimination which is comparable to a 50 % threshold when corrected for chance as was mentioned previously.

Difference thresholds are shown in Figures 10 and 11 for observers F.B. and D.W. respectively. Increment and decrement thresholds are plotted separately as a function of the comparison interval.

The increment difference thresholds are seen to be a U shaped function of comparison interval. As the comparison





interval increases from 0 to 30 msec, the increment difference threshold decreases. But as the comparison interval increases from 30 to 90 msec, the increment threshold increases. Both observers indicate a slight leveling of the threshold function between 45 and 60 msec.

There is not such good agreement between the observers with regards to the decrement thresholds. Observer F.B. shows an inverted U shaped threshold function while observer D.W. shows a U shaped function. Only at the 45, 60, and 75 msec comparison intervals do the two decrement threshold functions show a similarity.

### Discussion

The data from Experiment I indicated that the j.n.d. thresholds of temporal discrimination decreased monotonically as the interval within two pulse stimuli increased from 0 to 75 msec. However an analysis of this threshold function into separate functions for the increment and decrement difference thresholds suggested that threshold discrimination might be more complex.

The data from Experiment II bears out this suspicion. It shows that the increment and decrement difference thresholds clearly are not the same. This indicates that temporal acuity is not being limited by random noise but is more probably determined by the responsiveness of the visual system. Furthermore, by measuring the increment and decrement thresholds over a wider range of intervals, the second experiment shows that the increment threshold is a U shaped function of two-pulse interval with a minimum threshold at an interval of 30 msec.





The situation is not so clear with respect to the decrement threshold function. The data of both observers indicate that it is different from the increment threshold function. In general the decrement thresholds seem to be lower than the increment thresholds; this holds for both observers at the 45 and 75 msec intervals. The large difference between the observers at the 30 and 90 msec intervals is puzzling. It may be that the more experienced observer F.B. was able to utilize cues which were not recognized by D.W. Clearly further research is needed if we are to obtain optimally detailed knowledge of temporal acuity in the visual system.



## CONCLUSION

The results of Experiment I indicate that temporal acuity as measured both by temporal resolution thresholds and temporal difference thresholds is not significantly affected by stimulus luminance, provided this luminance is at least 50 mL.

The results of Experiment I and II indicate that temporal acuity does vary with the length of the stimulus interval being discriminated.<sup>3</sup>

The results of Experiment II indicate that the threshold for discriminating an increase in the interval between two light impulses is a U shaped function of that interval. Though there is still some doubt as to the nature of the threshold function for detecting a decrease in two pulse interval, the results of Experiment II show that these thresholds are different from the increment thresholds.

The classical concept of a difference threshold is that it arises from the organisms having to discriminate stimulus effects from random activity in its nervous system (Woodworth and Schlosberg, 1954). According to this concept the increment and decrement difference thresholds should be equivalent portions of the interval of uncertainty" surrounding a stimulus, and the best measure of the difference threshold would therefore be obtained by averaging the absolute values of these thresholds.

The discovery that increment and decrement thresholds differ in slope and/or absolute level indicates that temporal difference thresholds are not merely a result of random activity. Rather, it would seem that these discriminations are determined by limitations in the visual processes which preproduce the temporal course of stimulation.

### Some Questions

What significance do these findings have for our knowledge of the processes that mediate temporal acuity?





It was observed in the present study that two pulse stimuli with very brief intervals appeared to be considerably brighter than stimuli with longer intervals. Kietzman and Sutton (1967) also noted that the apparent brightness of the stimuli was used by the observers to help make these temporal discriminations, in addition to the obvious cue of a two-flash effect. This brightness summation effect is a well known phenomena.

Bouman and van den Brink (1952) observed that within durations of 50 msec, two subthreshold light pulses could summate completely, to produce a stimulus of above threshold brightness. Across longer durations the chances of summation decreased and reached zero at about 110 msec. Nelson, Bartley, and Jewell (1963) studied the brightness effects produced by varying the duration of the dark interval between two pulses. Observers varied the brightness of a steady source to match the brightness of the two-pulse stimuli. The data showed an increase in brightness as the dark interval was reduced below 100 msec duration. In similar fashion Ikeda (1965) studied the summation effect of pairs of light pulses at two luminance levels above threshold. The observers reported the increment thresholds of brief test stimuli superimposed on the first and second pulses as the interval between pulses was varied from 0 - 100 msec. As the interval between pulses increased from 0 - 50 msec, the calculated brightness summation decreased from 100% to zero. Donchin and Lindsley (1965a) provide similar evidence for an increase in brightness as the interval between a pair of light pulses is decreased. Their observers gave psychophysical judgements of the changes in brightness of the first pulse as the interval between the first and second pulse was varied. Donchin and Lindsley (1965b) show that this brightness effect correlates with the magnitude of cortical evoked potentials.





On the basis of this evidence, it seems quite possible that temporal discrimination of two pulse stimuli could be partly mediated by a process which is similar to the brightness discrimination processes in the visual system.

If the temporal discriminations of the present experiment were made on the basis of stimulus brightness, and if stimuli with shorter intervals appear brighter, one might understand why temporal discrimination is worse for stimuli of shorter intervals: If shorter intervals appear brighter, a greater brightness difference might be necessary for their discrimination according to the classical Weber-Fechner Law. In the present experiment these brightness differences would result from changing the interval of the pulse stimuli. Since discrimination requires a greater brightness difference with shorter intervals, discrimination would therefore require a greater interval difference with shorter interval stimuli. Even though these discriminations are based on brightness, increasing the intensity of the stimuli would not change temporal discrimination as long as intensity had a linear effect on the brightness duration effect. Evidence supporting this assumption of a linear effect is provided by Graham and Kemp (1938). They found that brightness discrimination was unchanged by increase in intensity from 1- 200mL with stimuli varying in duration from 2 - 500 msec.

Work upon the brightness effects produced by two pulse stimuli suggests that the processes in the visual pathway which mediate temporal discrimination may be related to the processes which result in the summation of stimuli energy within short durations. What, then, are the processes underlying the sensory effect of brightness summation, and how might these relate to the present temporal discrimination data?



## Implications of the Alternation of Response Theory

Bartley's alternation of response theory suggests an explanation for brightness summation (Bartley, 1958; Bartley and Nelson, 1963; Bartley, 1964).

This theory recognizes that the visual pathway is comprised of a great number of parallel channels. A channel can be defined as a continuous neural connection between a locus on the retina and one or more loci in the cortex. A single channel is made up of several neurons which extend from the neural layers within the retina, up through the optic nerve, through lower centers in the central nervous system such as the lateral geniculate nucleus where branching may occur, and end in the cortex. While the existence of interconnecting neurons may alter the exact structure of channels under various conditions, under certain conditions these channels can be considered as being more-or-less stable as to structure and number.

The thresholds, latencies, and recovery times of these channels are not all identical but vary from channel to channel. As a result a brief photic stimulus impinging on the retina produces activity at the cortex which is distributed over a period of time which can be much greater than the duration of the original stimulus.

Nelson and Bartley (1964) discuss some implications that these facts have for visual brightness phenomena. In particular over short durations and slow frequencies of repeated stimulation, large bursts of massed activity are produced at the cortex because of a synchronous discharge of all channels activated by the stimuli. To the extent that stimuli can cause many channels to fire together at the cortex, that stimulus will be perceived as appearing brighter. This relation between the amplitude of cortical potentials and visual end result was suggested by Bartley in 1934.





The theory suggests that if two stimuli occur close together in time, the cortical distributions of channel activity will overlap producing a massed effect which is directly related to brightness. The theory also suggests that brightness will depend on a difference in the number of channels which are activated within some period by two or more stimuli. On this basis, the theory can explain how the activity produced by two pulse stimuli could summate to produce a brightness effect, which then could be the basis upon which two pulse stimuli are discriminated.

#### Implications of Brightness Discrimination Data

The possibility that temporal discrimination could be mediated at least partly by a brightness discrimination process does not necessarily prove that these discriminations are related. Is there any further justification for believing that these discriminations are similar? If this were the case, one would expect that brightness discrimination would also be a U shaped function of pulse interval, or, perhaps more generally, total stimulus duration.

Graham and Kemp (1938) found that at a given intensity brightness discrimination improved as the duration of a single pulse stimulus increased from 2 - 80 msec, but it remained constant with further increases in duration. However, at a given luminance level, the total energy of these stimuli was being increased as pulse duration was increased. This is not comparable to the equal energy stimuli used in the present study. But Graham and Kemp studied these effects at enough luminance levels so that it is possible to obtain from their data a picture of brightness discrimination as a function of duration by considering pulses of various luminances at various durations.



Using data for pulses of different luminance levels does, however, present another problem, since stimuli of different luminances would activate different channel populations - a situation which did not exist in the present study. Evidence such as that from Chang and Kaada (1949) indicates that the number of channels activated in the visual pathway increases more or less geometrically with luminance. Therefore the classical Weber ratio should serve to equate the effects produced by different luminances.

Table 7 shows the calculation of the Weber ratios of intensity discrimination,  $\Delta I/I$ , from the data of Graham and Kemp.  $\Delta I/I$  values were derived for intensities which would result in stimuli of equal energy at the durations used by Graham and Kemp. Figure 12 shows these  $\Delta I/I$  values plotted as a function of stimulus duration. Figure 12 indicates that brightness difference discrimination improves as the duration of the stimulus is increased up to 80 msec, but as stimulus duration is increased beyond this point discrimination worsens.<sup>4</sup>

The data on brightness discrimination therefore indicates a U shaped function which is similar to that found for temporal discrimination as the total durations of respective stimuli are varied.<sup>5</sup> This is further evidence that these discriminations may be mediated by processes which in fact are similar.

According to Bartley's alternation of response theory, brightness discrimination would depend on a difference in the number of channels which are activated by two stimuli. It is therefore possible to hypothesize that temporal acuity discrimination over short durations depends on some difference





being produced in the number of channels whose responses do or do not overlap at the cortex.

#### A Possible Explanation: Modeling of the Distribution of Cortical Activity

The optic nerve is composed of neural fibers whose diameters and transmission velocities vary over a wide range (Bishop and Bartley, 1934; Bishop and Clare, 1955; Lennox, 1958; among others). While most of these physiological studies have employed rabbits and cats, Chacko (1948) presents similar anatomical evidence for the optic nerve in humans. Noda and Iwama (1967) find evidence for a similar variation in the fibers connecting the terminus of the optic tract in the lateral geniculate with the visual cortex.

Bishop and O'Leary (1936, p. 295-296) point out some consequences of these facts for the activity produced at the cortex by afferent stimulation. "As the mass impulse, starting as a synchronous activity in parallel axons of the optic nerve, passes along fibers having different conduction rates, and across synapses having different accessibilities, the individual elements of the responses will be progressively dispersed, the synchronous volley be modified to a scattered distribution in which the individual responses will overlap and be summated to form a longer lasting potential."

Some general implications for the sensory end result of such a distribution of cortical activity have been stated in the alternation of response theory discussed previously. Blackwell (1963) also discusses some implications of these facts for brightness discrimination of single and double pulse stimuli.



But, specifically, what does the distribution of channel velocities imply for the temporal discrimination of two pulse stimuli?

The data of Bishop and Clare (1955) and Noda and Iwama (1967) on the latencies of cortical responses to brief stimuli show that the distribution of the delayed activity is more-or-less continuous and skewed towards shorter latencies. Though the exact distribution of the latent responses within the human visual pathway is currently undeterminable, anatomical evidence indicates that it is similarly skewed. However, as a first approximation to the exact distribution, let us assume a normal distribution of channel velocities and consequent latencies of cortical response.

Consider a brief light pulse presented at time  $t = t_1$ . This pulse peripherally activates a local set of channels in the visual pathway whose thresholds are equal to or below the energy of the pulse.<sup>6</sup> A normal distribution of the transmission rates of these channels would imply that their responses would arrive at the cortex in a distribution such as shown in Figure 13 - A.

A second pulse of equal energy is now presented to the same locus some time later at time  $t = t_2$ . Assuming that the average recovery period of the channels is small in relation to the interval of the pulses, the distribution of activity at the cortex would be similar to the distribution produced by the first pulse. The means of these two distributions would, however, be separated by an interval equal to the interval of the initiating pulses as shown in Figure 13 - B.





As the interval between the first and second pulses is increased, the distributions of activity produced by them overlap less and less, while the amount of nonoverlapping activity increases. See Figure 13 - C. What does this overlapping and nonoverlapping of cortical responses imply for the sensory end result produced by the two pulses?

Variation in the transmission rates within the visual pathway distributes, over time, the cortical responses to brief light pulses. This distribution effect means that some cortical responses to two light pulses may occur simultaneously even though the pulses were separated in time. Not only should this affect temporal resolution, but it also implies that variation in only the temporal parameter of stimulation produces something more complex than a simple corresponding temporal variation in sensory end result. This overlapping of responses suggests that amplitude as well as intermittancy of temporal activity is influenced by the interval of the pulses.

Bartley (1934) proposed that a direct relation existed between the amplitude of cortical activity and the brightness effect of a stimulus. Recent studies by Bartlett and White (1965) and Donchin and Lindsley (1965b) seem to confirm this. Furthermore, White and Eason (1966) report a direct relation between the perceived numerosity of a number of photic pulses and the intermittancy of their cortical potentials.

These studies indicate that the sensory effects of brightness and number are related to the summation and differentiation of their cortical responses. Therefore there is good reason to





believe that: 1) To the extent that the distributions produced by two pulses overlap, the sensory end result will be a single flash of enhanced brightness. 2) To the extent that they do not overlap, the result will be two flashes.

But even at large intervals the distributions of Figure 13-C can be seen to overlap to some extent. Also for any non-zero interval, there should be some nonoverlapping activity. On what basis then does the visual system differentiate such distributions into the separate end results of brightness and twoness?

#### The Problem of Differentiation and Integration in the Visual System

It is likely that brightness as a sensory end result is overwhelmingly determined by the magnitude of activity produced in the central nervous system of an intact organism. Adrian and Matthews (1927) first observed that the intensity of stimulation correlated with the frequency of discharges in the optic nerve. Later Bartley (1934) observed a direct relation between stimulus brightness and the amplitude of cortical evoked potentials. Recent research by Donchin and Lindsley (1965b) indicates that the effective brightness of stimulus inputs is related to the amplitude of activity produced at the cortex.

Yet in either the terminology of perception or physics magnitude of energy has no meaning unless this magnitude is specified relative to the dimension of time. Any attempt to define the magnitude of some energy implicitly involves an integration of this energy over some unit of time.

With a physical system there is no problem in finding a unit



of time which is relevant to the other units of the measure. For example the physical analog of brightness, intensity, is definable as joules/sec which is a measure of work done over a period of one second. However things are not so convenient when one attempts to define brightness relative to a perceptual system. What unit of time should be used so that the definition will be relevant to the other sensations of the observer.

This problem is usually avoided by defining brightness relative to the physical units of a light source which the observer reports as having a similar effect. This method of definition will suffice as long as it is related to other variables external to the organism. But this physical definition of a perceptual magnitude will not suffice when one is addressing the sensory end result per se. Whenever one considers the relationship between the physiological activity produced by a stimulus and the accompanying sensory end result, one encounters the problem of over what time period the physiological activity is integrated or differentiated to produce the sensation. As Bullock (1966) points out, there are numerous physiological mechanisms which could accomplish the necessary integration. However, the question remains: which combination of these mechanisms is relevant to the sensory end result?

Since the physiological alternatives are many, let us instead consider some of the possible characteristics of how a sensory integrative process could differentiate between simultaneous and nonsimultaneous neural activity. As was pointed



out in the previous section, two distributions of activity (such as the normal distributions of Figure 12 - C) will continue to overlap to some extent as the separation between their means is increased. Somewhere there should be an average cutoff point where two distributions no longer effectively overlap.

This cutoff point might occur when the level of activity in the first distribution or in the joint distribution drops below a certain level. In this case the cutoff point would be equivalent to the "protection level" of a statistical test as discussed by Edwards (1963). Garner's (1962) discussion of noise and redundancy in biological information systems suggests that this protection level might be fairly high in order to reduce uncertainty.

A second possibility is that the cutoff point is temporally determined as occurring at some period of time after the onset of stimulation or after activity has reached a maximum. Such an effect would be equivalent to a short term buffer storage such as discussed by Arronson(1967).

A third possibility is that the cutoff point is determined independently of stimulus activity by some autonomous, periodic integrative process. This would be similar to the sensory scanning model suggested by Stroud (1956) and further discussed by Blackwell (1963), Treisman (1963), and White (1963). However- this scanning mechanism would have to operate at a considerably faster rate than the 10 cps mechanism discussed in these studies.

A fourth possibility may also exist. The sensory end result from simultaneous and nonsimultaneous activity might be determined in a purely probabilistic manner contingent on the total activity present at any instant; a possibility suggested by Brunswick (1951).







The above possibilities suggest different mechanisms by which the visual system may integrate simultaneous and differentiate nonsimultaneous activities. But until definitive details are forthcoming, this mechanism may be said to operate so that 1) the greater the overlap in activity, the greater the likelihood that summation of two distributions will occur; and 2) the less the overlap, the greater the likelihood of two separate effects. There seems no reason not to grant these as being general properties of a sensory pathway, indeed they are implicit in all of the above theories.

#### The Model Continued

We can now continue to explore the implications of normal distributions of cortical activity, bearing in mind the above considerations of how the visual system probably differentiates between simultaneous and nonsimultaneous activity.

In order to predict the discriminability of two-pulse stimuli having various pulse intervals, let us consider how the amounts of overlapping and nonoverlapping activities change as pulse interval is varied.

Figure 14 - A shows how the amounts of overlapping and nonoverlapping activities would vary as a function of pulse interval. The units along the Y axis can not of course be specified, but it is assumed that an increase in amount of activity is based on an increase in the number of channels whose responses do or do not overlap. As pulse interval increases the responses produced by the second pulse will overlap with fewer responses produced by the first pulse. The form of these curves



was obtained by considering the change in nonoverlapping activity as analogous to the change in the power of a statistical test to discriminate two normal distributions as the difference between their means is increased, (Hays, 1963).

To determine from Figure 14 - A the difference threshold for a two-pulse stimulus of some given interval, the rate of change in overlapping and nonoverlapping responses must be derived. (It may be recalled that, just prior to the introduction to this model, it was hypothesized that temporal discrimination depended on some difference occurring in the number of channels whose responses did or did not overlap. Therefore it follows that the smallest difference pulse interval will be detectable at that interval where the number of overlapping and nonoverlapping channels changes most rapidly as pulse interval is changed. At that particular interval a small change in interval will result in a large change in total activity and hence a small difference threshold.)

Figure 14 - B shows the rate of change of overlapping and nonoverlapping activities. The changes of both activities are identical since they derive from a common neural pool. Both show a small rate of change when the second pulse occurs immediately after the first pulse. The rates of change increase with increase in pulse interval reaching a maximum at the point of inflection of Figure 14 - A. On the basis of the assumptions made so far, this inflection point would correspond with the moment when the distribution of responses to the first pulse reaches a maximum. At this interval the difference thresholds





reach a minimum. At still longer pulse intervals, the rate of change decreases. Since both rates of change are similar, their summated rate of change will also be a U shaped function of similar temporal characteristics.<sup>7</sup>

We are now ready to return to the original hypothesis that temporal, as well as brightness, discrimination depends on some difference in the number of channels whose responses overlap. The question of simultaneity and lack of physiological data prevent specifying what this difference actually is. Therefore let us make the simplest assumption possible, namely that the necessary difference is some constant amount across all intervals.

From Figure 14 - B it is possible to derive the relative change in pulse interval which will produce a constant difference in activity even though the magnitude of the difference is unknown. The more rapidly the overlapping and nonoverlapping response activities are changing, the smaller the change in interval which is required to produce some constant difference in activity. These considerations lead to difference thresholds which are a U shaped function of pulse interval as shown in Figure 14 - C.

The above derivation of the difference threshold function will, however, only hold if the necessary difference in channel activity is negligibly small in comparison with the number of channels involved. There are good reasons for suspecting that this was not the situation in the present study. Small areas of stimulation and moderate luminance levels were used. This





means that the population of channels involved was fairly limited. Also the measured difference thresholds were of the order of tens of milliseconds in duration, which suggests that the change necessary for discrimination is not insignificant.

In order to see what might happen in a more finite situation where the necessary change in channel activity is substantial in relation to the number of channels involved, let us attach some hypothetical numerical values to a figure representing the amount of overlapping and nonoverlapping activity as a function of pulse interval.

Such an example is shown in Figure 15 - A. From this it can be seen that a decrease in pulse interval of 5 msec at a 30 msec interval results in an increase of 2 channels which produce overlapping responses and a decrease of two channels which produce nonoverlapping responses. The total change in both types of activity is 4 channels.<sup>8</sup> But an increase in pulse interval of 5 msec at the 30 msec interval results in a decrease of 4 channels which produce overlapping responses and an increase of 4 channels which produce nonoverlapping responses. The total change produced by an increase in interval is 8 channels as compared with a change of 4 channels produced by a decrease. It can be seen that a similar but opposite effect would occur at a pulse interval of 60 msec.

If a change of ten channels were required to produce a detectable change in stimulus effect (or to produce a threshold probability of detection), it should be apparent from the above discussion that a greater decrease than increase in pulse inter-



val would be required for discrimination at the 30 msec interval. At the 60 msec interval a smaller decrease than increase would be required. The resultant difference thresholds are seen to be different depending on whether the difference is produced by a decrease or increase in pulse interval. These thresholds have been referred to in the present study as decrement and increment thresholds respectively.

These considerations lead to a finite model of two-pulse difference thresholds as shown in Figure 15 - B. Increment and decrement thresholds are seen to be intersecting U shaped functions of pulse interval. For pulse intervals shorter than that interval where the difference thresholds are at a minimum, the decrement thresholds increase faster than the increment thresholds as pulse interval is decreased. For pulse intervals longer than this interval, the decrement thresholds increase more slowly than the increment thresholds as pulse interval is increased. The magnitude of the difference between the increment and decrement thresholds would, of course, depend on the actual difference in activity required for discrimination and the number of channels involved.<sup>9</sup>

The above discussion has attempted to derive a model of processes that could mediate temporal discrimination in the visual system. As yet the model is little more than an outline for these processes. But let us see how its predictions and assumptions compare with some relevant data.

#### Implications of Data for the Model

The data of the present study support the following predictions of the model: 1) The increment thresholds of temporal





acuity are a U shaped function of pulse interval. 2) The increment and decrement thresholds are different. 3) The minimum increment threshold occurs at a pulse interval of 30 msec.

The first two points should be evident from the discussion to Experiment II. The third requires further explanation to see its significance.

In the description of the model on page 50, it was pointed out that the difference thresholds would reach a minimum at an interval where overlapping and nonoverlapping response activity was changing most rapidly. This interval was seen to correspond in Figures 13 and 14 with the time at which the distribution of delayed responses reached a maximum at the cortex. Is there any evidence that latent responses at the cortex reach a maximum 30 msec after a stimulus is presented?

Noda and Iwama (1967) studied the latency of response to a brief light pulse by single cells in the lateral geniculate nucleus. They found that the number of responding cells reached a maximum between 20 and 30 msec after the stimulus. Since their study used rats, the corresponding latencies in the human would be slightly longer. Though it is not conclusive, this data on the latent responses in the lateral geniculate nucleus does agree with what the model predicts on the basis of the present temporal discrimination.

The data of the present study also raise some questions with regards to the model. Some of these questions center on the decrement threshold function. The model predicts that: 1) The decrement thresholds should be a U shaped function of pulse in-





terval similar to the increment threshold function. 2) The decrement and increment functions should reach a minimum at the same pulse interval.

The ambiguity of the decrement threshold data does not permit either of these predictions to be tested. For example, while the data of observer D.W. in Figure 11 shows a U shaped decrement function which is roughly parallel to the increment function and tends to support the model, the data of observer F.B. in Figure 10 indicates an inverted U shaped function for the decrement thresholds and does not support the model. Further data must be obtained before the predictions of the model with respect to decrement thresholds can be tested.

Other questions also arise with regards to the exact form of the threshold functions. As it stands, the model predicts that these should be simple U shaped functions. Yet the data on the increment thresholds seem to indicate a function which is more complex. Such difficulties for the model may be cleared up by considering the assumptions of the model in greater detail.

One of these assumptions was that the actual distribution of neural transmission rates could be approximated by a simple normal distribution. The normal distribution was used as a convenient first approximation with the hope that it might indicate the general nature of these threshold functions. The next step would be to take into account the skewness towards shorter latencies which is indicated by the data of Noda and Iwama (1967).



If the model were based on a similarly skewed distribution, the effect would be to skew the predicted threshold functions so that the minimum thresholds occurred at shorter pulse intervals. This effect does seem to approach the obtained data more closely than the predictions of a simple normal distribution.

Ideally one would want to use the actual distribution of neural transmission rates as the basis of the model. While this information is currently unobtainable for humans by any direct measures, the inverse of this approach suggests another application for the model: With rigorous measurements of the two pulse difference thresholds, it should be possible to predict the actual distribution using the principles suggested in the model. This suggests that the model could be developed by an iterative process of approximating the distribution of neural transmission rates on the basis of data, and subsequently determining how well this approximation can predict similar data.

Another assumption of the model was that the recovery periods of the neural channels were short enough so that all channels could be reactivated by the second pulse. While the recovery periods of single neurons are a matter of only a few milliseconds, the recovery periods of their synaptic connections are more appreciable. Therefore the assumption may not be valid for the shorter pulse intervals.

Burke and Sefton (1966) studied the recovery times to optic nerve stimulation of individual cells in the lateral geniculate nucleus of rats. They observed that the P cells (87% of all cells) require about 20 msec to reach full recovery. This





suggests that a similar recovery effect probably occurs in the human visual pathway. Therefore some error is introduced into the model by assuming that this neural recovery effect is negligible.

If channels have not recovered from the effects of the first pulse, the effects of the second pulse will be diminished. As a result the recovery of the channels would contribute to the changes that result in sensory discrimination. The rate of recovery at short intervals would interact with the rates of change of overlapping and nonoverlapping responses to produce a more rapid change in activity as pulse interval is varied. For the model this would mean that the difference thresholds would be somewhat reduced at the shorter intervals. This effect might also account for some of the deviation from a simple U shaped function observed at the shorter intervals in the present study.

The model also did not consider the effects which would be produced by a periodic variation in the sensitivity of neurons at various stages within the visual pathway. Such an effect would further modulate the sensory end result produced by overlapping and nonoverlapping responses.

Evidence for such an effect was discovered by Bartley and Bishop (1933) and shows up consistently in evoked potential data. Chang's (1950) data indicate that cortical rhythms begin to show their effects on cortical responses to two-pulse stimuli around 60 msec after the onset of the stimulus. Laufer and Verzeano (1967) discuss the evidence for such periodic activity occurring along the entire visual pathway. The effects of such





periodicities is also evident in sensory threshold data (Blackwell, 1963; Boyton, 1961) and in studies relating sensory effectiveness to cortical activity (Donchin and Lindsley, 1966).

In his study of brightness discrimination, Blackwell (1963) describes how a six cycle per second periodic process seems to be interacting with the processes of brightness discrimination. If a similar process is also affecting temporal discrimination, it could be readily added to the model as a central effect which modulates the distributions of cortical activity. Applied to the present study this could account for some of the deviation from a simple U shaped function which was observed at the longer pulse intervals.<sup>10</sup>

The model states that the separate effectiveness of the second of two pulses is an ogival function of pulse interval. (note the amount of nonoverlapping response activity in Figure 14 - A.) There are physiological and sensory data which seem to support this contention.

Chang (1950) measured the cortical responses to a pair of .1 msec sound pulses as the interval of these pulses was increased from 0 to 300 msec. He measured the magnitude of the second cortical response as a function of pulse interval. His results show that the magnitude of the second cortical response is an ogival function which increases as pulse interval increases up to 80 msec. The inflection point of his curve seems to occur at a pulse interval of about 30 msec. This is approximately the interval at which the model would predict such an inflection point both on the basis of the present temporal discrimination data and on the basis of the latency distribution curve of Noda and Iwama (1967).



The sensory threshold data by Sperling (1965) is relevant to this discussion. He measured the threshold energy of a test light pulse at various intervals after an initial pulse. Sperling found an accelerating decrease in threshold energy as pulse interval was increased up to 100 msec. Above threshold data with similar implications was obtained by Ikeda and Boyton (1965) using a brightness increment threshold measure. The duration of a relatively darker interval between two brighter stimuli was varied from 2.8 to 91 msec. Within this darker interval the increment threshold was found to decrease as the interval increased.

These studies provide physiological and sensory evidence which is in accordance with the model's statement of how the separate effectiveness of the second of two pulses increases with increase in pulse interval.

The model also states that the summation effect produced by two pulses should decrease in an ogival function as pulse interval is increased. (Note how the amount of overlapping activity changes in Figure 14 - A.) Though the physiological data of Chang (1950) does not indicate any appreciable decrease in the magnitude of the response to the first pulse, there is considerable sensory evidence for this effect.

Several studies (Bouman and van den Brink, 1952; Donchin and Lindsley, 1965a; Ikeda, 1965, and Nelson, Bartley, and Jewell, 1963) which report a decrease in the brightness effect of two-pulse stimuli as pulse interval is increased have already been mentioned. Of these the study by Ikeda (1965) shows functions which are clearly ogival. The inflection points of Ikeda's data also occur at about 30 msec, which





corresponds with what was just mentioned concerning Chang's data on overlapping responses.

These studies provide evidence which is in accordance with the model's statement of how the summation of two light pulses decreases as their interval increases.

A final assumption of the model was that two stimuli could be discriminated if their cortical response distributions differed by some amount. The necessary difference in response activity was assumed to be a constant. The validity of this type of an assumption may never be directly verifiable since it seeks to relate physiological activity to sensory end result. Rather the validity of this second assumption must rest on its usefulness in predicting sensory discrimination data.

Some insight into this problem may, however, be gained by considering again the fact that luminance level does not significantly affect temporal discrimination.

According to the assumptions of the model, an increase in stimulus intensity would be accompanied by an increase in the number of activated channels and a corresponding increase in the amount of cortical activity. There seem to be two hypotheses which could account for the fact that temporal discriminations are unaffected by such an increase in activity.

The first, and apparently simplest, hypothesis is that the difference in activity required for discrimination also increases with an increase in the amount of activity. This hypothesis suggests that the discriminable difference is not a fixed constant but rather depends on some percentage of the total





activity present. This would account for the lack of an intensity effect at any given pulse interval. But it also predicts that decreases in pulse interval also would not effect discrimination since the visual system supposedly could not distinguish an increase in activity produced by an increase in intensity from an increase in activity produced by the summation of two pulses. This prediction is contrary to the temporal discrimination data, and therefore we can, at least tentatively, reject this hypothesis of a variable necessary difference.

The second hypothesis is that distributions of activity produced by various intensities all have the same variance. According to this hypothesis, as pulse interval is increased, the rate of change of activity would be the same at all intensities. Thereby discrimination would not be affected by intensity as long as the difference required for discrimination remained constant at all intensities. The second hypothesis is therefore more in agreement with the model.

If intensity did not alter the variance of the cortical activity but only the amount of activity, one would expect that intensity level would not interact with pulse interval (or in some cases stimulus duration) during brightness discrimination.

When the results of the present experiment were examined in terms of a simple brightness discrimination phenomena, it was suggested that the lack of an effect would occur if intensity had a strictly linear effect on the processes underlying brightness discriminations. This suggestion was supported by Graham and Kemp's (1938) data, which showed that brightness discrimination at various durations was unchanged by variations in intensity above 1 mL.



Similar evidence that intensity does not interact with stimulus duration can be noted in other studies on visual discrimination. Sperling (1965) measured the changes in threshold energy of a test pulse at various intervals following an initial pulse whose intensity was varied. While the absolute magnitude of the test pulse thresholds necessarily increased with increases in intensity of the initial pulse, as pulse interval was increased the rates of change of these thresholds remained constant at all intensity levels. Baker (1953) measured the threshold of a test pulse at various intervals after the offset of a continuous stimulus of various intensities. While intensity of the continuous stimulus displaced the curves showing dark adaptation, these curves were essentially parallel for intensities above 3.1 Trolands.

Since only pulse interval affects temporal discrimination and since intensity does not interact with pulse interval during brightness discrimination, only pulse interval must be affecting the variance of the distribution of cortical activity. This evidence lends support to the second hypothesis which suggested that a constant difference in activity mediated temporal discrimination.

Though this evidence is not conclusive, (there may be other hypotheses which would also work) this evidence does support the assumptions of the model regarding the relation between physiological activity and sensory end result. Furthermore, the second hypothesis indicates how the model could account for the lack of an intensity effect on temporal discrimination.



In conclusion, the model does seem to offer an explanation for the major phenomena of temporal discrimination which were reliably demonstrated in the present study. Several assumptions and implications of the model are also supported by additional sensory and physiological data. Such data also suggest directions in which the model could be made more explicit. Since the model agrees with more general theoretical systems such as Bartley's alternation of response theory, and since it can relate to other models of sensory discrimination such as Blackwell's model for brightness discrimination, it may be worthwhile to develop the model further.





## SUMMARY

This study presents the first data about the difference thresholds of two-pulse temporal acuity for stimuli shorter than 100 msec. The difference thresholds were studied because it was believed that such data would indicate the temporal response characteristics of processes in the visual system which mediate temporal discrimination.

An electronic and optical apparatus system was designed, built, tested, and used to present two-pulse stimuli of controlled temporal, spatial, and energy characteristics.

A three position, temporal forced-choice procedure was used in order to obtain the most sensitive measure of the difference thresholds.

Experiment I studied two-pulse difference thresholds for pulse intervals of 0, 15, 30, 45, 60, and 75 msec. A balanced factorial design was employed so that each interval was compared for threshold determination with every other interval. Two groups of observers were presented two pulse stimuli at luminance levels of 50, 200, and 2000 mL; 200mL being observed in common.

Stimulus intensity was found to have no significant effect on the performance of the observers. This finding for difference thresholds agrees with the effects of intensity on resolution thresholds which have been reported previously.

The results of the first experiment also indicated that the difference thresholds decreased monotonically as two-pulse interval was increased. However, a closer analysis of the data re-



vealed that the increment and decrement threshold functions might be more different than alike. Therefore a second experiment was proposed to investigate this matter in greater detail.

Experiment II studied the increment difference thresholds for two-pulse stimuli with intervals of 0, 15, 30, 45, 60, 75, and 90 msec. The decrement difference thresholds were studied with intervals of 30, 45, 60, 75, and 90 msec. A single stimulus luminance level of 500 mL was used.

In the second experiment it was found that the increment and decrement thresholds did differ. Increment thresholds were a U shaped function of pulse interval with a minimum at 30 msec. The exact nature of the decrement threshold function could not, however, be determined. The data of one observer showed a W shaped function, while that of the other showed an inverted U shaped function. There was, however, good correspondence on the mid range intervals from 45 to 75 msec.

Discovery that the increment and decrement thresholds differ indicates that these difference thresholds are not merely the result of noise or random activity in the visual pathway. Rather, it would seem that these discriminations are limited by distinct processes in the visual system.

Observations in the present and previous two-pulse threshold studies indicated that a brightness summation phenomenon was taking place during these discriminations. It was thought that this might be a clue to the sensory processes involved. Information on the brightness discrimination of stimuli comparable to those of the present study was calculated



from the data of Graham and Kemp (1938). The similarity these brightness data to the present temporal data suggested that the processes mediating temporal discrimination might be similar to processes mediating brightness discrimination.

The alternation of response theory holds that brightness discrimination depends on the number of channels and distribution of activity in the visual system. It was hypothesized that temporal discrimination might also involve a change in the number of channels.

Two assumptions were made with regards to the alternation of response theory: 1. The latencies of channels in the visual system are normally distributed. 2. A fixed change in the distribution of the cortical activity of channels would result in a discrimination at all two pulse intervals. On the basis of these assumptions a model was developed to explain the processes mediating temporal discrimination. This model predicted not only that the increment and decrement thresholds were different, but also that the increment thresholds were a U shaped function of pulse interval.

Some physiological and perceptual data from other studies were discussed relative to the model. These seemed to support the assumptions and implications of the model. Attempts to develop this model further pointed out the need for additional research on the relations between physiological activity and sensory experience.







## FOOTNOTES

- <sup>1</sup> One could also apply the concept of temporal acuity to the discrimination of more than two successive events. For example Geldard (1953) suggests flicker fusion as such a measure. For the present however, we shall mainly be concerned with the simplest case - the discrimination of two events whose energy is distributed over time. (p.2)
- <sup>2</sup> Decrement thresholds for the 30 msec comparison interval were measured with test stimulus intervals of 22.5, 11.5, and 0 msec. (p. 32)
- <sup>3</sup> The study by Kietzman and Sutton (1967) indicates that it is the total duration (pulse interval plus pulse durations) rather than the pulse interval alone which is a primary factor in temporal discrimination. However, since only pulse interval was varied in the present study, we shall continue to discuss the subject relative to pulse interval to avoid confusion. But it should not be forgotten that as pulse interval is varied, total duration is also varied. With pulse durations of only 1 msec, the error either way is not very great. ( p.36)
- <sup>4</sup> Similar evidence can be obtained from the data of Keller (1941), however her intensity and duration values do not provide as many equal energy points as that of Graham and Kemp. (p.42)
- <sup>5</sup> Unfortunately Graham and Kemp do not show increment and decrement threshold data separately, rather these were presumably averaged as in the traditional method of determining difference thresholds. In view of the present finding that temporal increment and decrement thresholds are different in shape and/or level, it might be worthwhile to investigate whether Graham and Kemp type brightness difference thresholds can not be similarly resolved. It would seem that such a study could have important implications for knowledge about the processes mediating brightness discrimination. (p.42)
- <sup>6</sup> For the moment we can ignore the distribution of channel thresholds since stimulus intensity has little effect on temporal acuity. (p.44)
- <sup>7</sup> Some additional considerations, to be discussed shortly, indicate that they may be displaced somewhat relative to each other. (p.51)
- <sup>8</sup> More explicitly, in view of the simultaneity question, the decrease in pulse interval of 5 msec has resulted in a change in probability of the two types of activity. And the magnitude of this change in probability is equivalent to the change which would be produced by 4 channels as described. (p. 52)



- <sup>9</sup>The suggested difference between increment and decrement thresholds is relevant only when these are measured with respect to a common comparison stimulus. This is not to suggest that increment and decrement thresholds, per se, must differ. In the example of Figure 15 a pulse interval 5 msec shorter than a 30 msec interval produced activity which was less different from that of the 30 msec two-pulse stimulus than the activity produced by a two pulse stimulus whose pulse interval was 5 msec longer than a 30 msec interval. Therefore the model predicted that a greater decrease than increase in pulse interval would be required for a difference threshold with respect to a 30 msec comparison stimulus. If threshold discrimination occurred with a stimulus whose pulse interval was 20 msec shorter than the 30 msec comparison stimulus, this decrement threshold should not, according to the model, differ from an increment threshold which is measured by using a 10 msec comparison stimulus and increasing pulse interval. The increment and decrement thresholds are expected to be 20 msec in both cases since stimuli with pulse intervals of 10 and 30 msec produce activity which is discriminably different. These considerations point out the importance of defining the comparison stimuli when thresholds are measured using a forced choice technique. In the present study the comparison stimuli were defined as those stimuli which were repeated twice on each trial and which were not changed from trial to trial within any block of observations. (p. 53)
- <sup>10</sup>Since there is considerable evidence that periodic phenomena do modulate the sensory effects of stimuli which extend beyond 100 msec in duration, it would seem worthwhile to extend the temporal threshold measures of the present study out to intervals of several hundred milliseconds. Such data ought to show this periodic effect and might provide further insight into this question. (p. 58)





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T A B L E S  
AND  
F I G U R E S



Table 1: Percent Correct Discrimination by  
the High Intensity Group

Intensity:								
Observers:	EH	CL	TN	$\bar{X}$	EH	CL	TN	$\bar{X}$
Comparison Interval								
Test Interval								
0 msec								
15 msec	40%	25	55	40	35%	30	30	31.7
30	35	35	45	38.3	55	40	65	53.3
45	50	65	75	63.3	75	50	80	68.3
60	70	80	95	81.7	90	70	95	85
75	100	75	90	88.3	95	85	100	93.3
15 msec								
0	25	45	35	35	35	45	35	38.3
30	35	30	40	35	30	15	70	38.3
45	45	65	75	61.7	65	35	75	58.3
60	75	55	90	73.3	70	75	85	76.7
75	95	63	90	82.7	95	75	100	90
30 msec								
0	50	40	22	37.3	45	55	50	50
15	40	20	40	33.3	25	30	45	33.3
45	40	60	55	51.7	35	40	50	41.7
60	75	55	95	75	50	40	60	40
75	100	70	95	88.3	90	45	90	75
45 msec								
0	50	54	63	55.7	65	45	90	66.7
15	55	55	40	50	35	65	85	61.7
30	35	20	25	26.7	35	50	55	46.7
60	80	20	75	58.3	35	35	60	43.3
75	90	50	95	78.3	90	35	75	66.7
60 msec								
0	85	70	90	81.7	75	70	95	80
15	75	65	90	76.7	80	65	95	80
30	55	70	75	66.7	55	55	85	65
45	75	45	65	61.7	45	50	55	50
75	35	60	65	53.3	40	30	25	31.7
75 msec								
0	90	75	85	83.3	90	80	100	90
15	95	85	90	90	100	70	95	88.3
30	90	80	90	86.7	90	53	95	79.3
45	100	55	85	80	85	55	90	71.7
60	80	65	80	71.7	85	40	40	55





Table 2: Percent Correct Discrimination by  
the Low Intensity Group

Intensity:									Groups Total Average
Observers:	MF	BN	AW	$\bar{X}$	MF	BN	AW	$\bar{X}$	
Comparison Interval									
Test Interval									
0 msec									
15 msec	30%	50	35	38.3	35%	45	35	38.3	37.1
30	50	40	45	45	45	45	35	41.7	44.6
45	50	85	75	70	45	80	50	58.3	65.0
60	75	95	85	85	75	100	75	83.3	83.8
75	70	100	80	83.3	85	95	80	86.7	87.9
15 msec									
0	15	25	25	21.7	25	30	40	31.7	31.7
30	20	35	40	31.7	25	45	35	35	35
45	55	90	65	70	45	80	45	56.7	61.7
60	70	100	70	80	45	90	60	65	73.7
75	95	100	65	86.7	75	100	75	83.3	85.6
30 msec									
0	40	50	55	48.3	45	60	75	60	48.9
15	45	45	40	43.3	30	35	35	33.3	35.8
45	35	50	35	40	20	60	35	38.3	42.9
60	50	90	55	65	45	85	45	58.3	62.1
75	90	100	60	83.3	50	100	80	76.7	80.8
45 msec									
0	75	65	75	71.7	75	80	55	70	66
15	75	75	70	73.3	75	80	50	68.3	63.3
30	30	55	45	43.3	35	35	50	40	39.2
60	25	40	20	28.3	0	50	30	26.7	39.2
75	85	90	30	68.3	45	75	50	56.7	67.5
60 msec									
0	95	100	80	91.7	95	100	100	98.3	87.9
15	80	75	100	85	85	95	85	88.3	82.5
30	65	80	70	71.7	70	75	70	71.7	68.8
45	50	65	35	50	60	50	55	55	54.2
75	75	60	35	56.7	30	60	35	41.7	45.8
75 msec									
0	80	100	100	93.3	75	100	95	90	89.2
15	85	100	100	95	85	90	90	88.3	90.4
30	90	95	75	86.7	70	95	100	88.3	85.3
45	79	100	74	84.3	45	90	65	66.7	76.9
60	75	90	65	76.7	40	40	45	41.7	62.1



Table 3: Analysis of Variance of High and Low Intensity Groups

High Intensity Group

Source	Sum of Squares	d.f.	Mean Square	F	p
Intensity	99.8	1	99.8	.73	.25
Observers	10271.1	2	5135.6	37.4	.01
Intervals	60512.1	29	2086.6	15.2	.01
Inty X Obs	298.2	2	149.1	1.08	.25
Inty X Intv	5404.6	29	186.4	1.35	.10
Obs X Intv	10340.6	58	178.3	1.29	.10
Error	7943.4	58	137.0		

Low Intensity Group

Source	Sum of Squares	d.f.	Mean Square	F	p
Intensity	836.4	1	836.4	3.25	.05
Observers	9307.9	2	4654.0	18.1	.01
Intervals	74740.5	29	2577.3	10.0	.01
Inty X Obs	581.6	2	290.8	1.13	.25
Inty X Intv	3802.6	29	131.1	.51	.25
Obs X Intv	9280.8	58	160.0	.62	.25
Error	14923.4	58	257.3		



Table 4: Analysis of Variance of High and Low Intensity Groups, Cont'd

Both Groups at 200 mL

Source	Sum of Squares	d.f.	Mean Square	F	p
Groups	.9	1	533.9	.20	>.25
Error	10802.8	4	2700.7		
Intervals	68416.8	29	2349.2	16.9	<.01
Group X Intv	3914.1	29	135.0	.88	>.25
Error	17446.2	114	153.0		

Groups Separately at 2000 and 50 mL

Source	Sum of Squares	d.f.	Mean Square	F	p
Intensity	249.6	1	249.6	.10	>.25
Error	9655.1	4	2413.8		
Intervals	64269.9	29	2216.2	12.8	<.01
Inty X Intv	3712.2	29	128.0	.75	>.25
Error	20025.8	114	175.7		





Table 5: Difference Thresholds and Analysis of Performance of Selected Observers

Difference Thresholds (in Msec)

Intensity: 2000 mL				200 mL						50 mL			
Observers: CL (EH) (TN)				CL	(EH)	(TN)	(MF)	(BN)	AW	MF	(BN)	AW	$\bar{X}$
Comparison													
0 msec	47	58	41	57	43	32	55	39	41	56	39	55	44
15	--	41	26	42	35	14	42	24	45	56	24	51	29
30	42	26	19	--	36	33	36	21	--	--	19	33	27
45	--	11	12	--	24	21	26	23	28	27	25	--	20
60	45	17	17	50	37	21	22	17	29	25	25	27	22
75	37	11	11	57	10	23	12	9	18	33	23	31	14

Analysis of Variance (For circled Observers only)

Source	Sum of Square	d.f.	Mean Square	F	p
Observers	639.8	6	106.6	1.95	$>.10$
Comparison	3631.4	5	726.3	13.3	$<.01$
Lin.	1795.6	1	1795.6	32.8	$<.01$
Lin. Dev.	1835.8	4	458.9	8.4	$<.01$
Quad.	196.6	1	196.6	3.6	$>.05$
Cubic	196.8	1	196.8	3.6	$>.05$
Error	1641.3	30	54.7		



Table 6: Increasing and Decreasing Difference  
Thresholds Analyzed Separately

Obs.	Log Lum	Thres. Type	Comparison Interval					(msec) 75
			0	15	30	45	60	
E.H.	1.1	inc. dec.	+58	+41	+26	+11		
	2.1	inc. dec.	+43	+35	+36	+24	-21 -37	-11 -10
C.L.	1.1	inc. dec.	+47		+42		+50 -40	
	2.1	inc. dec.	+57	+42			-50	-37 -57
T.N.	1.1	inc. dec.	+41	+26	+19	+12		
	2.1	inc. dec.	+32	+14	+33	+21 -22	-17 -21	-11 -23
M.F.	2.1	inc. dec.	+55	+42	+36	+27	+12 -32	
	2.7	inc. dec.	+56	+56		+27	-25	-12 -33
B.N.	2.1	inc. dec.	+39	+24	+21	+24 -23	-17	
	2.7	inc. dec.	+39	+24	+19	+25 -25	-25	- 9 -23
A.W.	2.1	inc. dec.	+41	+35		+28		
	2.7	inc. dec.	+55	+51	+27 -39		-29 -27	-18 -31
Average (Absolute Values)		inc. dec.	46.9	35.5	28.8	22.1 23.3	31 28.4	22.9



Table 7:  $\Delta I/I$  for Equal Energy Stimuli of  
Various Durations - calculated from  
the data of Graham & Kemp (1938)

Log I (mL)	I (mL)	Duration (ms)	Energy (I X D)	Log I/I	$\Delta I/I$
1.67	47	2	94	-.22	.758
1.27	18.6	5	93	-.60	.251
0.86	7.2	13	94	-.91	.123
0.49	3.1	30	94	-1.16	.069
0.065	1.16	80	94	-1.32	.048
-0.33	.47	200	94	-1.27	.054
-0.73	.186	500	93	-1.11	.078





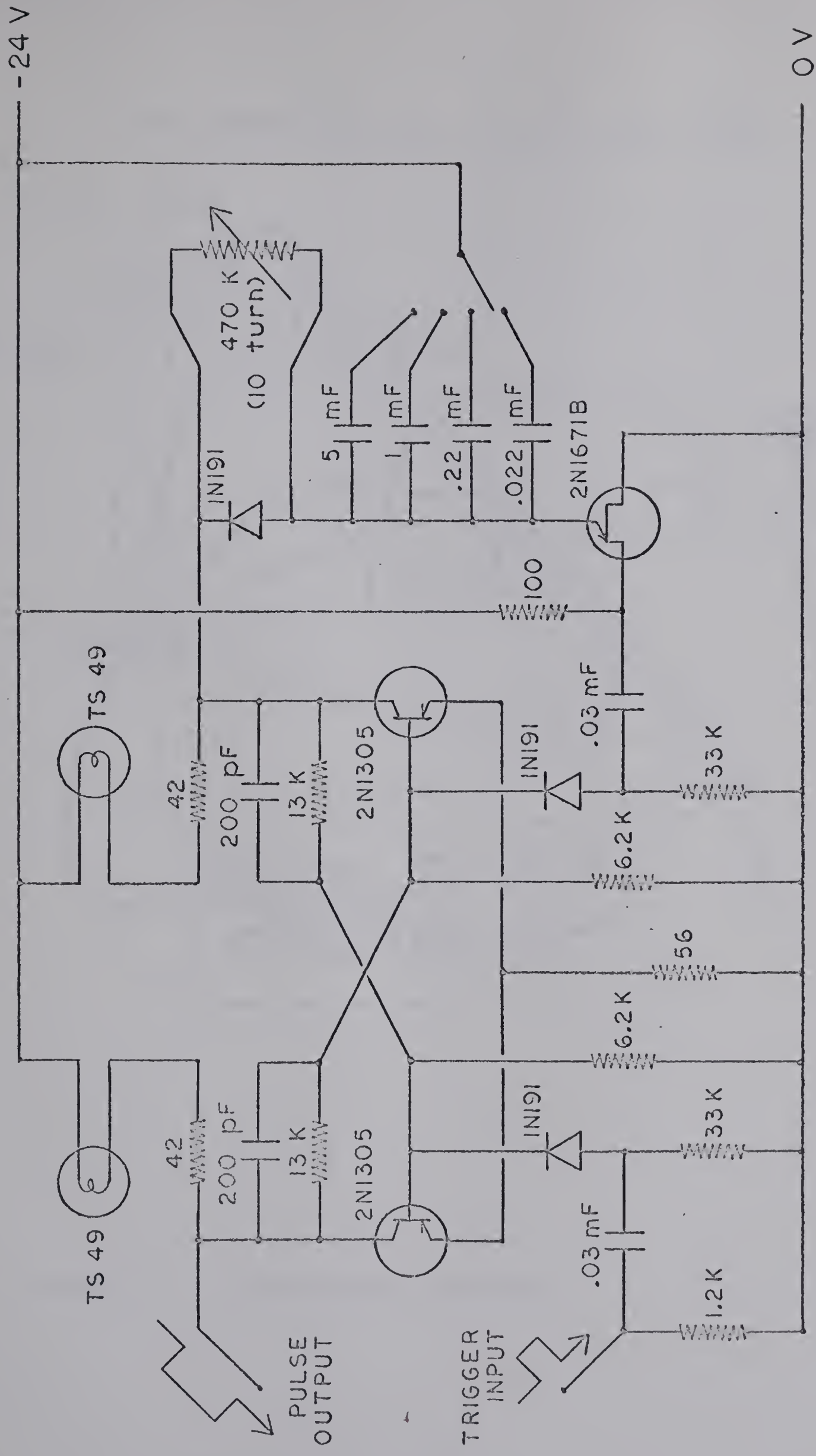


FIGURE 1 Circuit Diagram of the Electronic Timers which were Developed for this Study



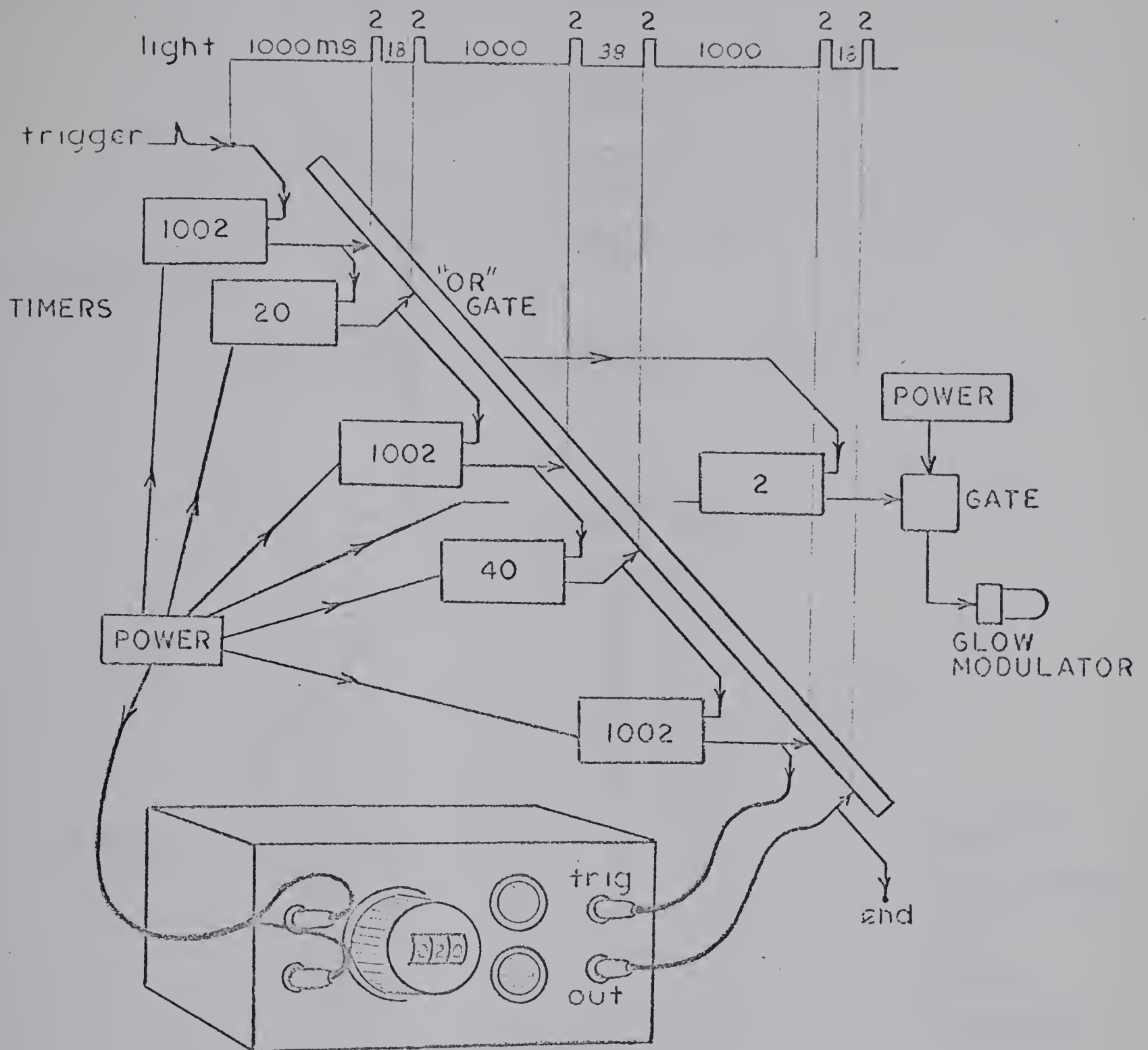


FIGURE 2 The Electronic Apparatus



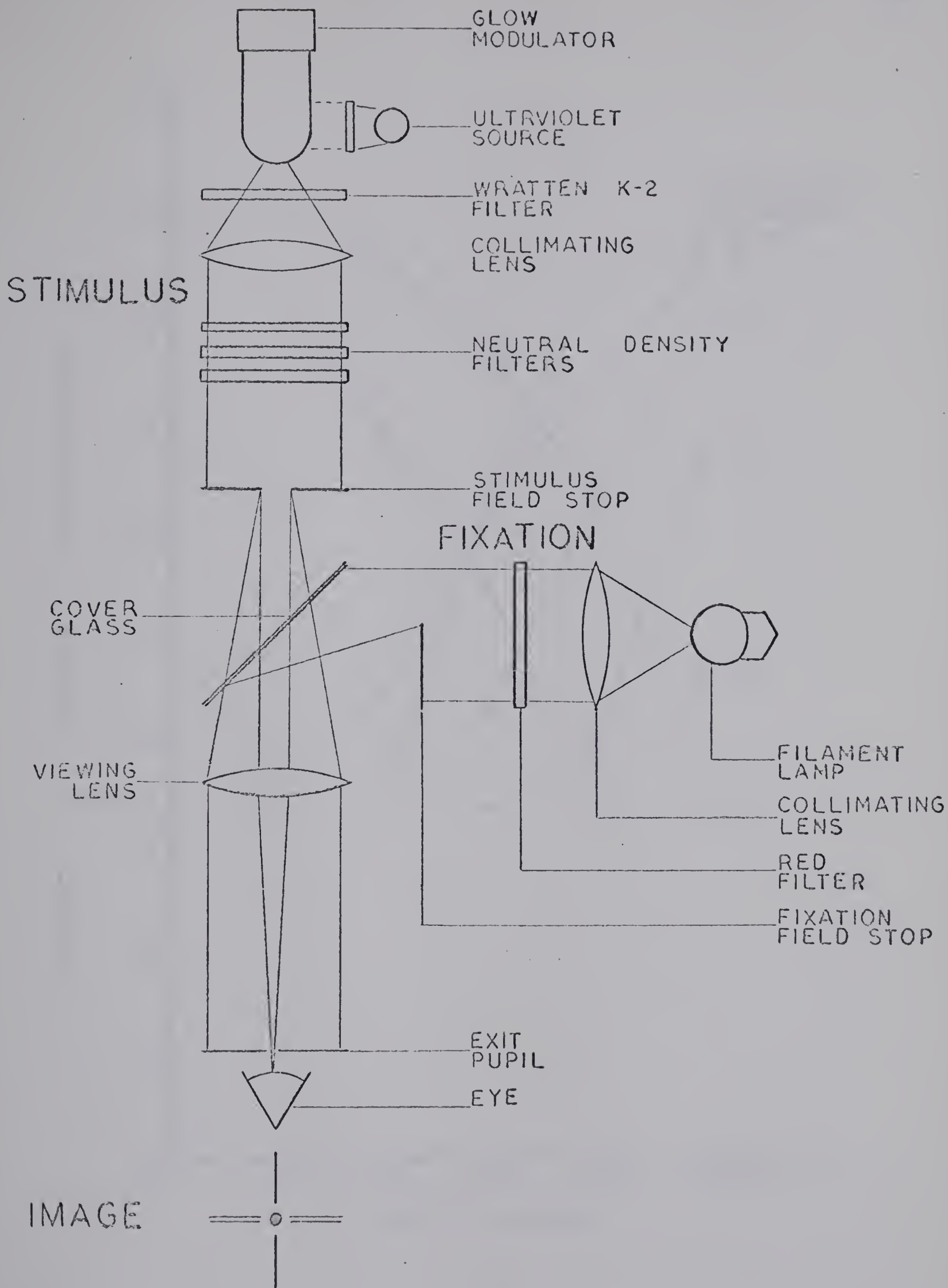


FIGURE 3 The Optical System





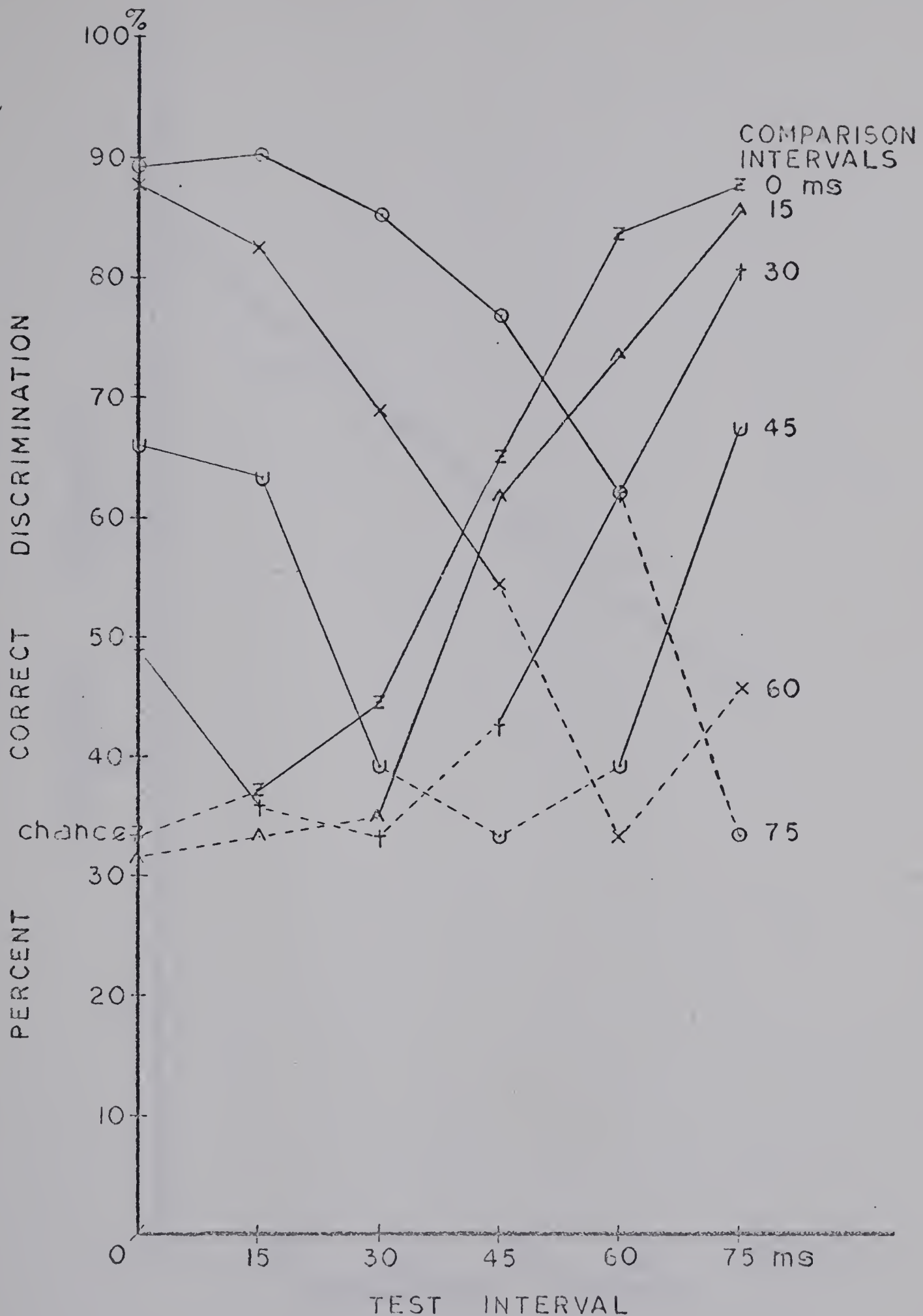


FIGURE 4 Discrimination of Two-Pulse Test Stimuli as a Function of Pulse Interval within Test Stimuli, shown for Comparison Stimuli of various Pulse Intervals, averaged over all Observers



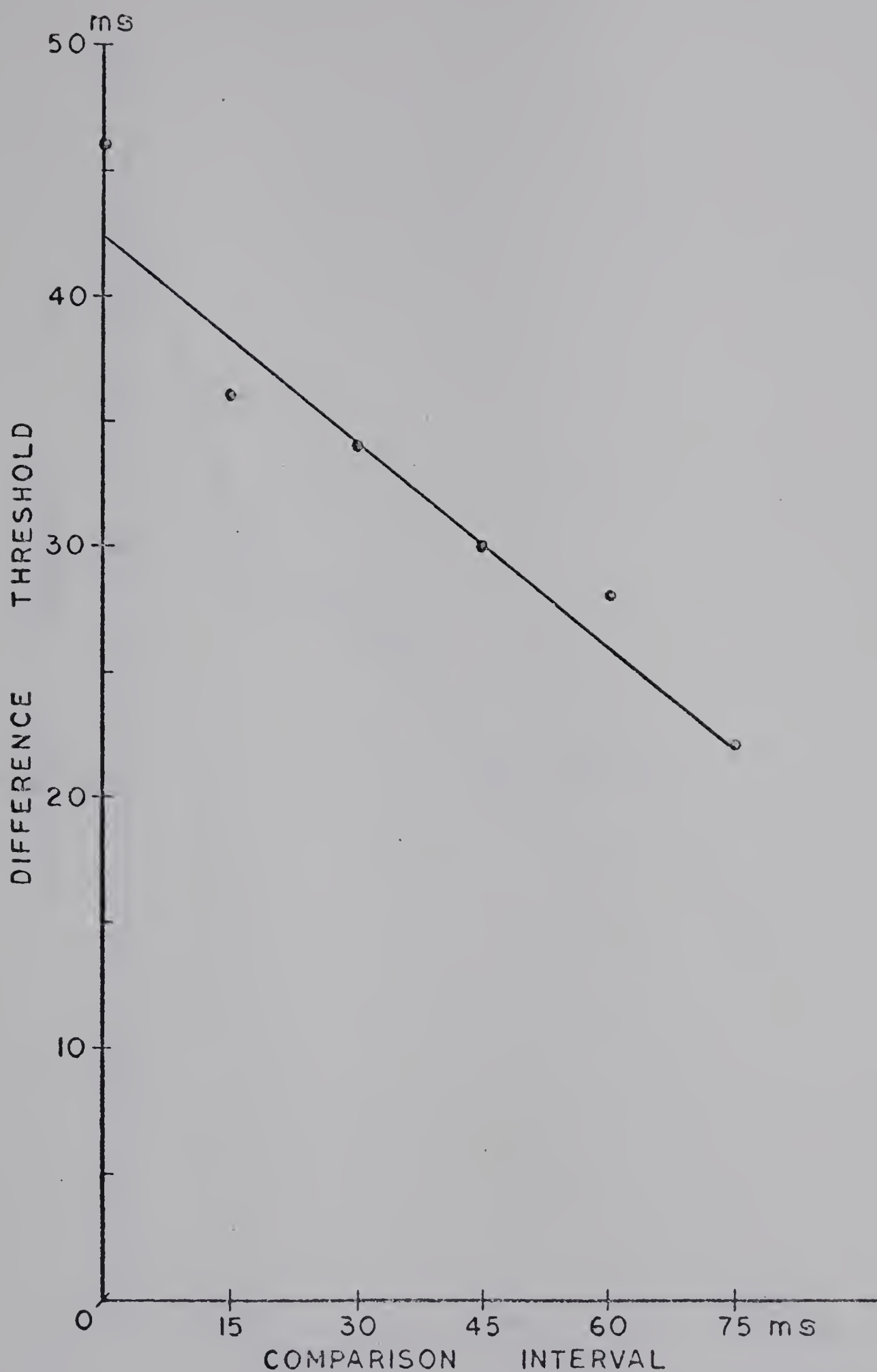


FIGURE 5 Difference Thresholds of Two-Pulse Stimuli as a Function of Pulse Interval within Comparison Stimuli



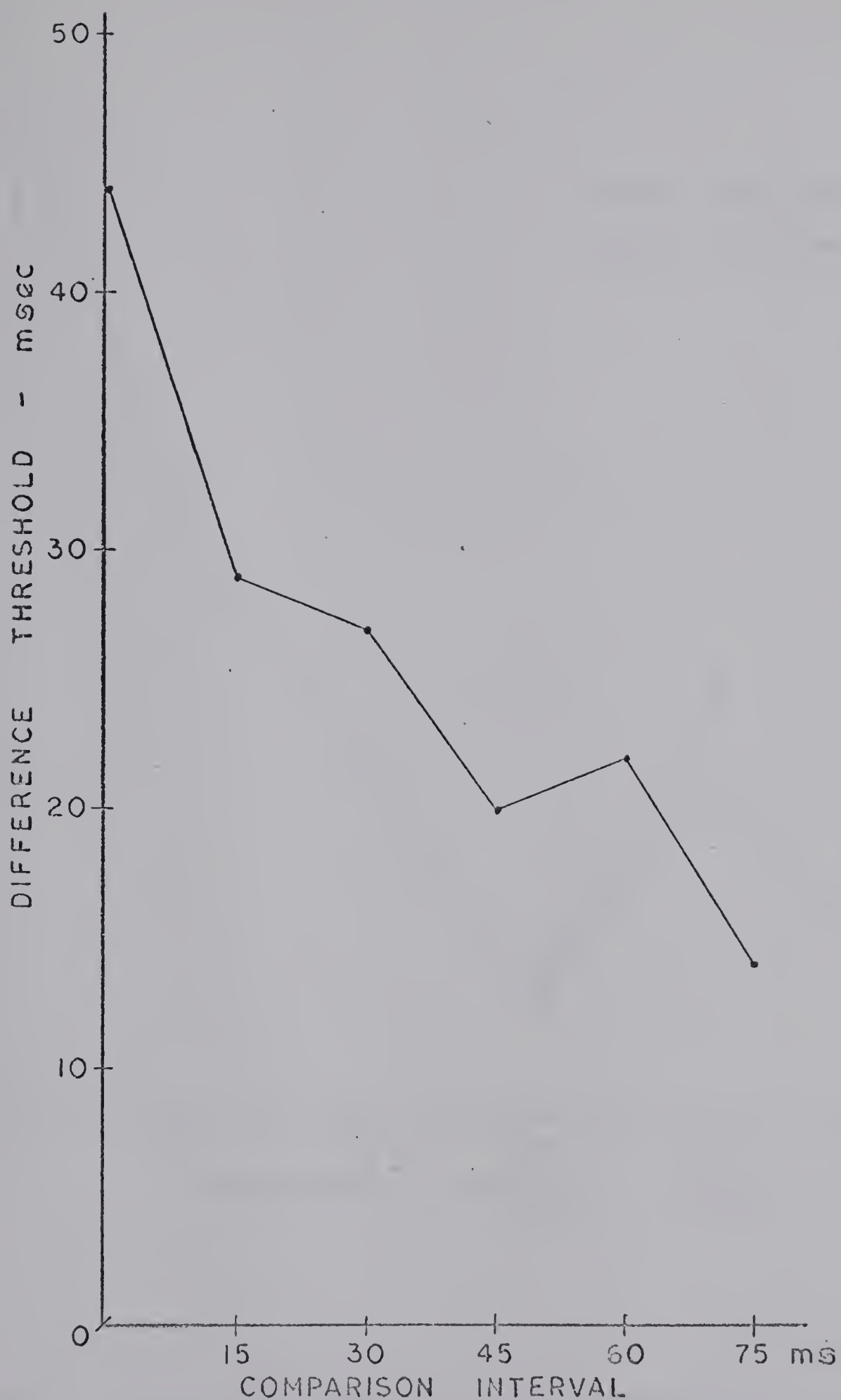


FIGURE 6 Difference Thresholds of Two-Pulse Stimuli as a Function of Pulse Interval within Comparison Stimuli, for Data used in Trend Analysis





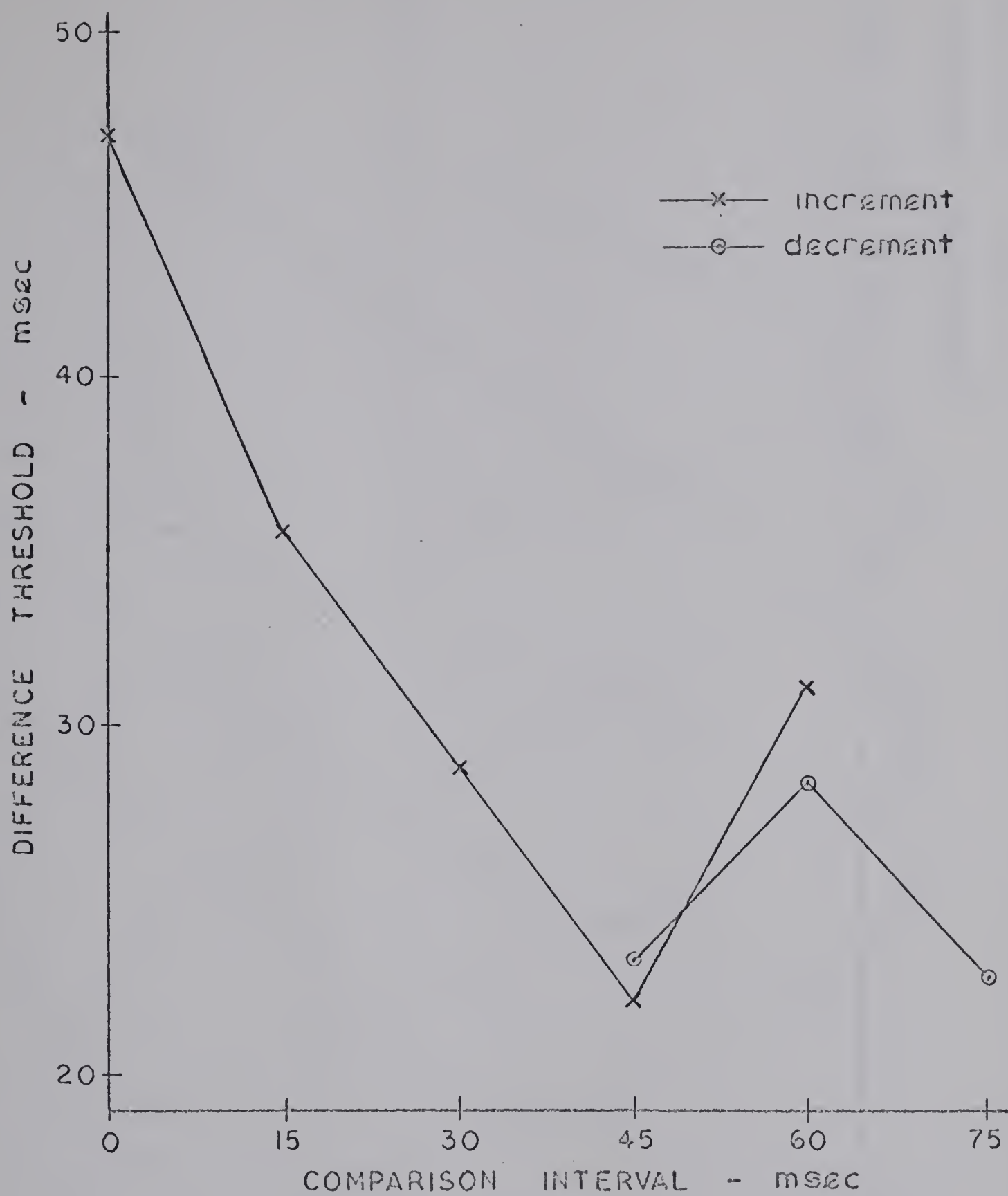


FIGURE 7 Increasing and Decreasing Difference Thresholds plotted Separately as a Function of Pulse Interval within Comparison Stimuli, averaged over all Observers



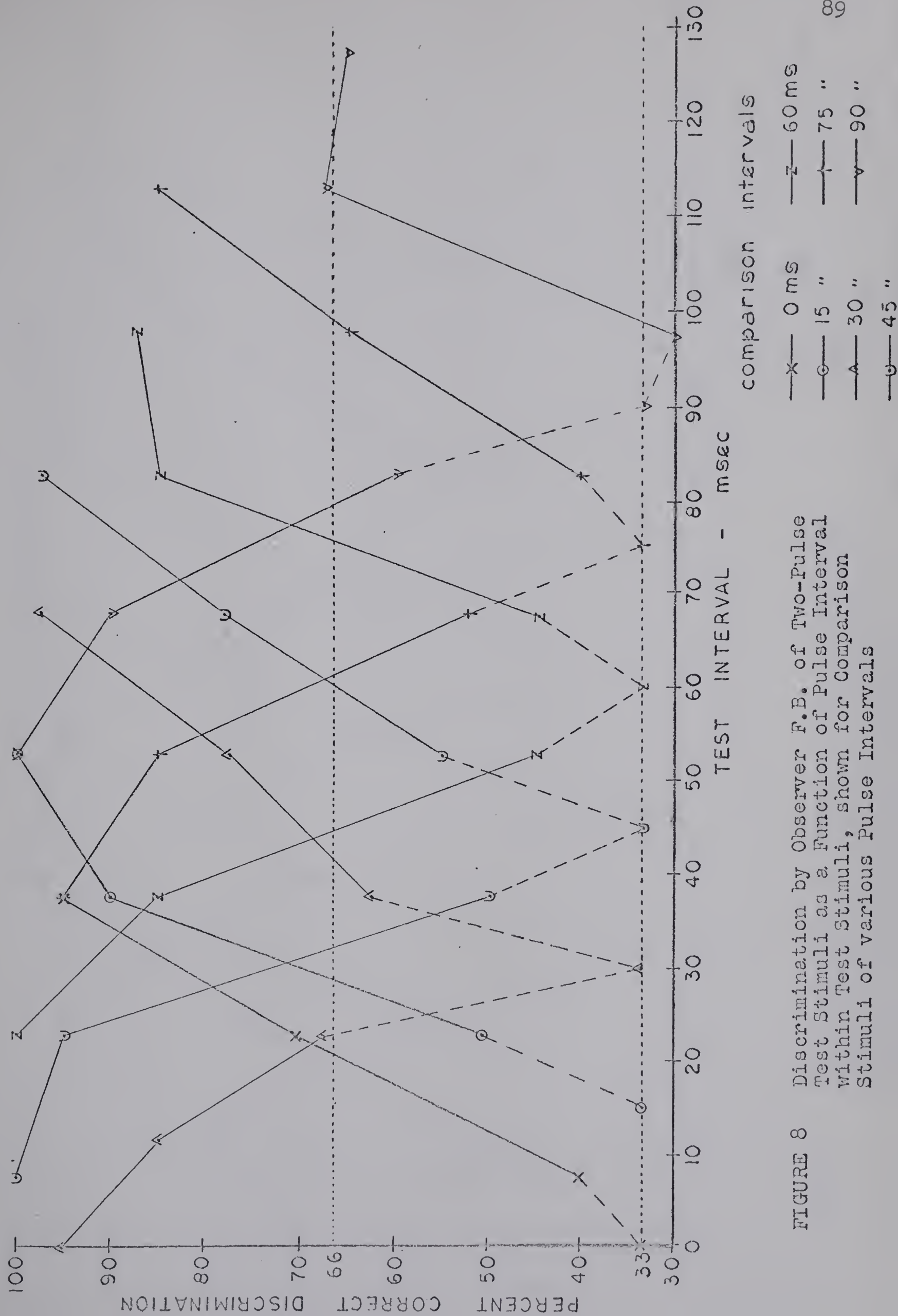


FIGURE 8 Discrimination by Observer F.B. of Two-Pulse Test Stimuli as a Function of Pulse Interval within Test Stimuli, shown for Comparison Stimuli of various Pulse Intervals



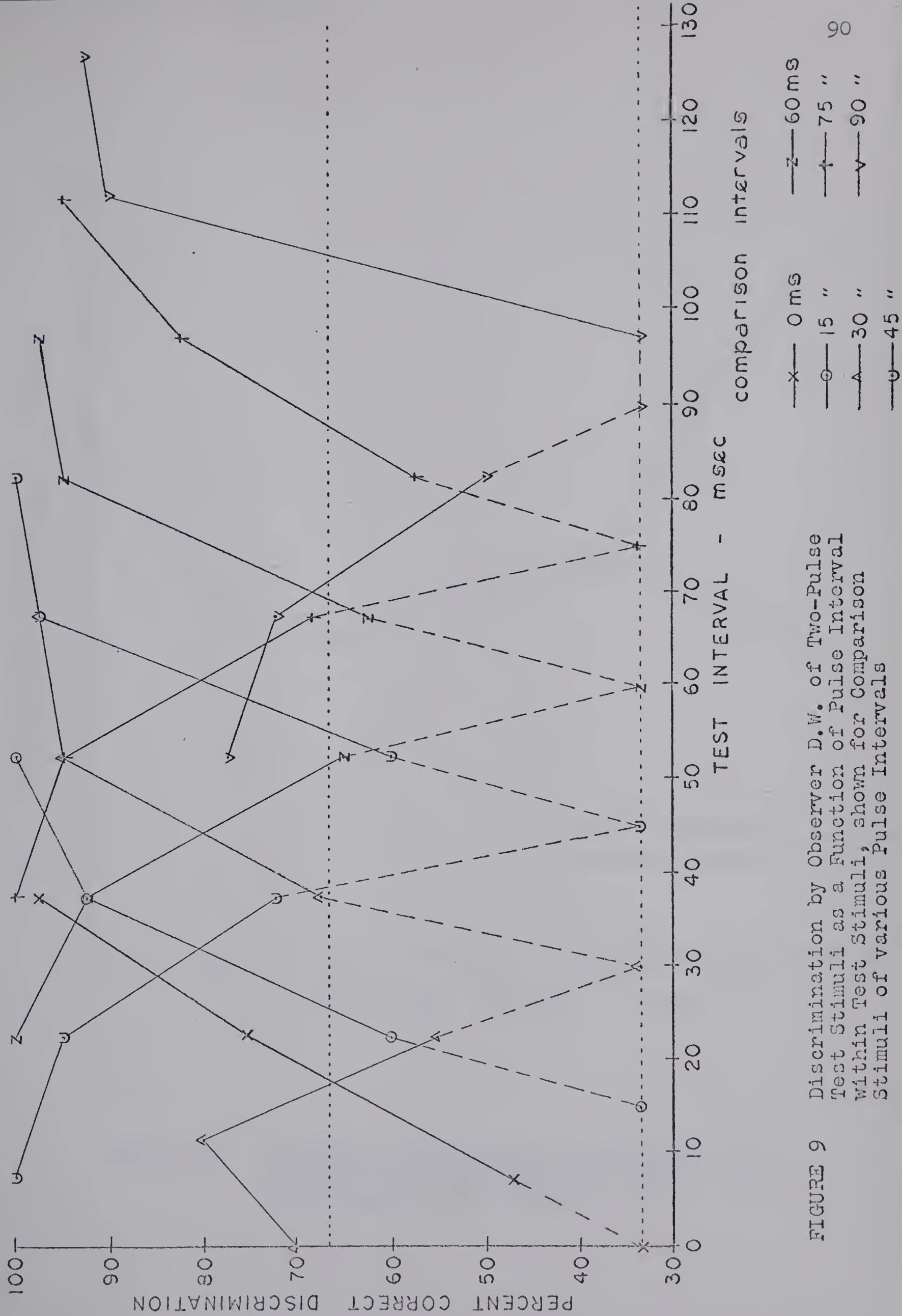


FIGURE 9 Discrimination by Observer D.W. of Two-Pulse Test Stimuli as a Function of Pulse Interval Within Test Stimuli, shown for Comparison Stimuli of various Pulse Intervals





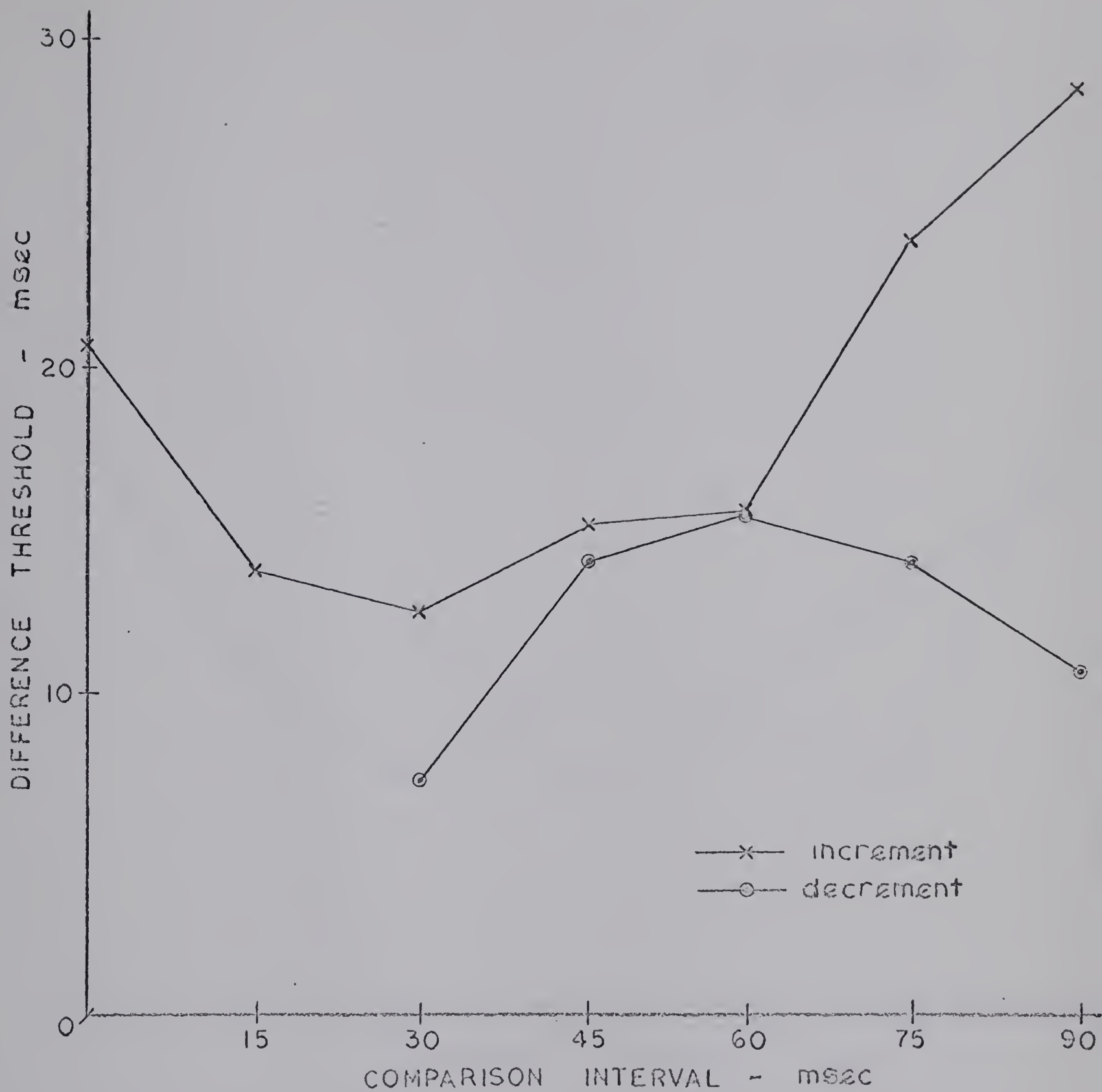


FIGURE 10

Increment and Decrement Thresholds as a Function of Pulse Interval within Comparison Stimuli, for Observer F.B.



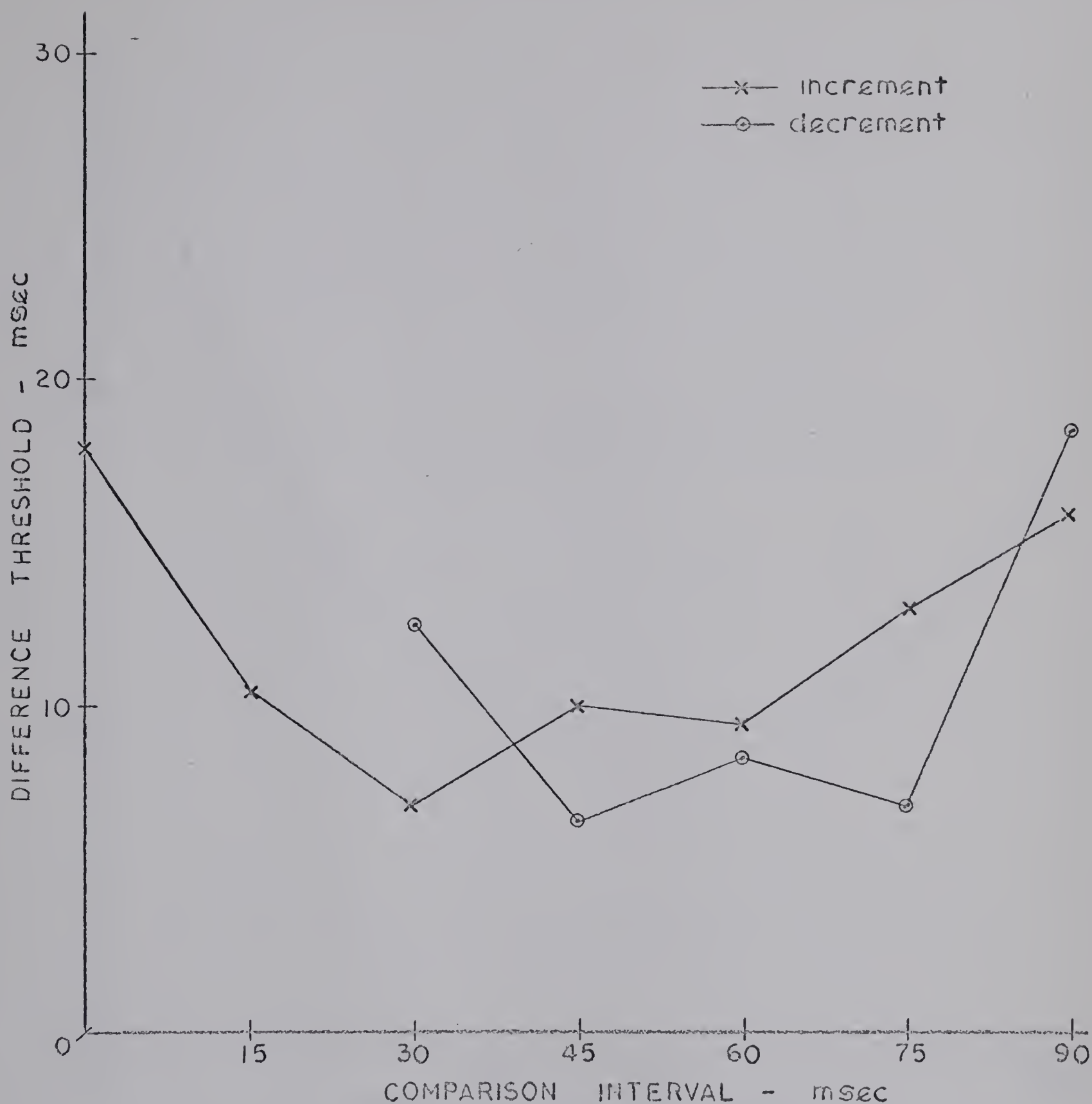


FIGURE 11

Increment and Decrement Thresholds as a Function of Pulse Interval within Comparison Stimuli, for Observer D.W.



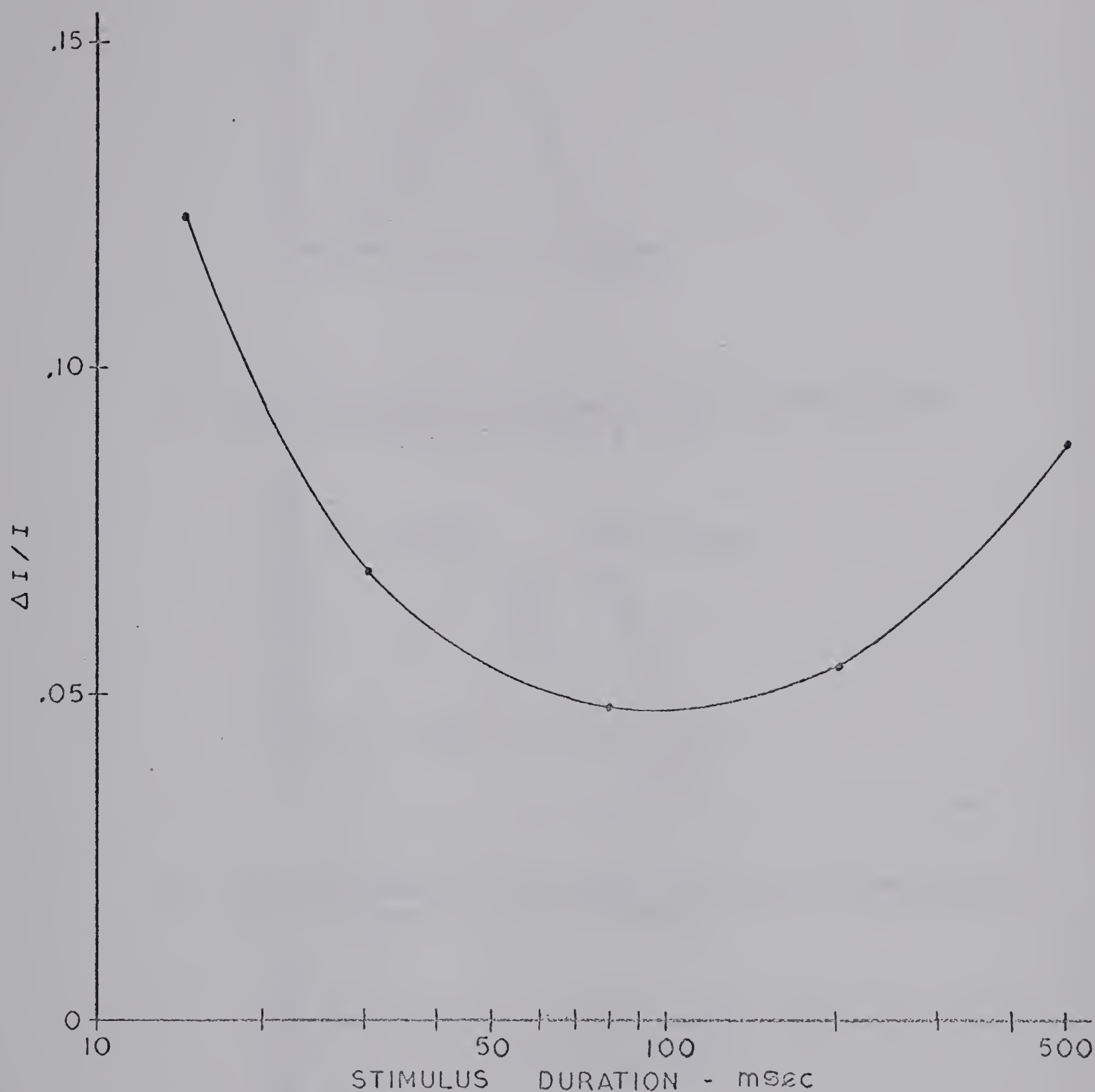
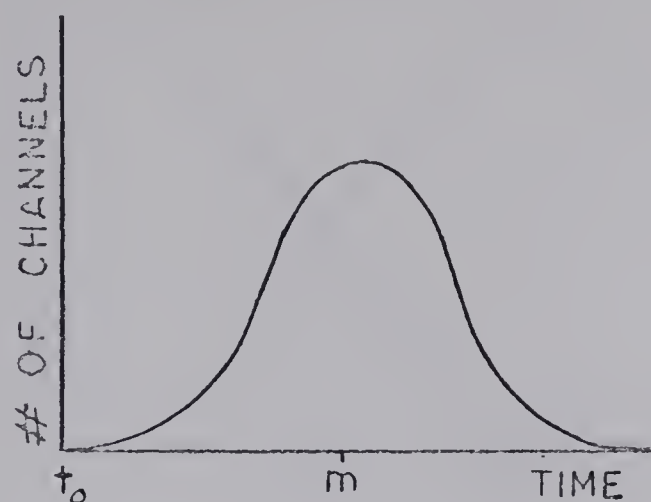


FIGURE 12 Brightness Discrimination,  $\Delta I / I$ , as a Function of Stimulus Duration, for Stimuli of Equal Energy, calculated from the Data of Graham and Kemp (1938)

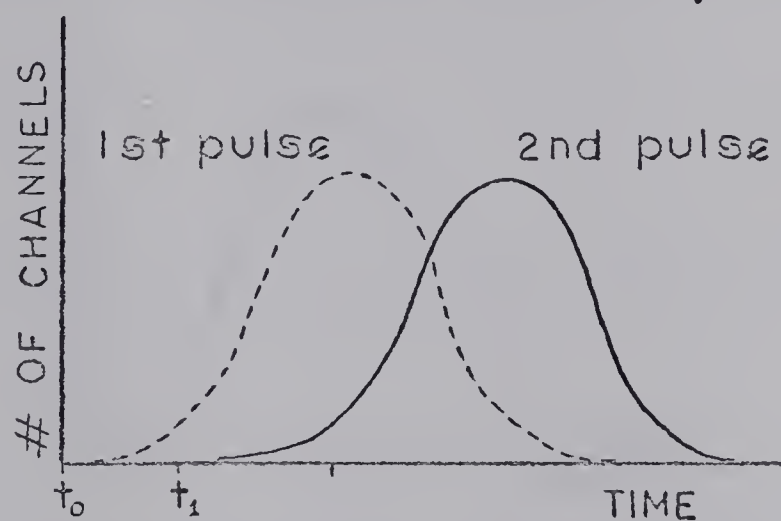




A - Distribution of cortical response activity to a single light pulse which occurred at time  $t = t_0$



B - Distribution of responses to a second pulse which occurred at time  $t = t_1$



C - Distribution of responses as time of occurrence of the second pulse is varied

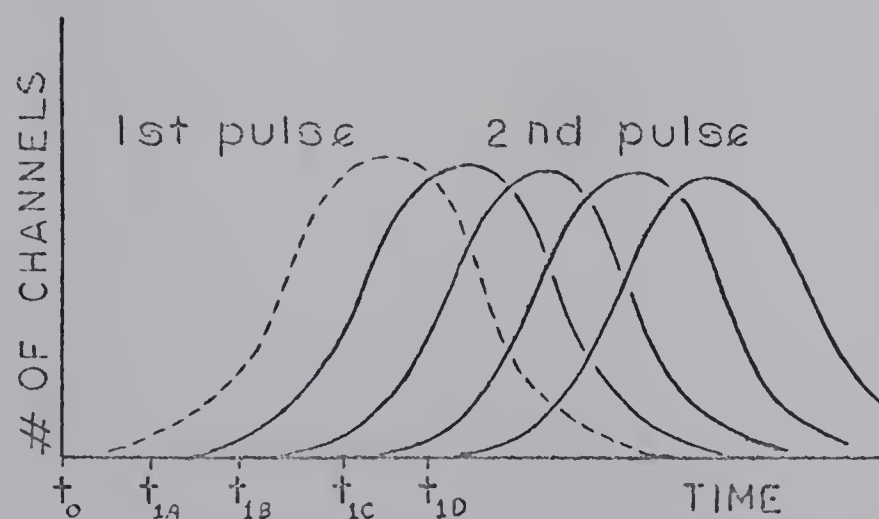
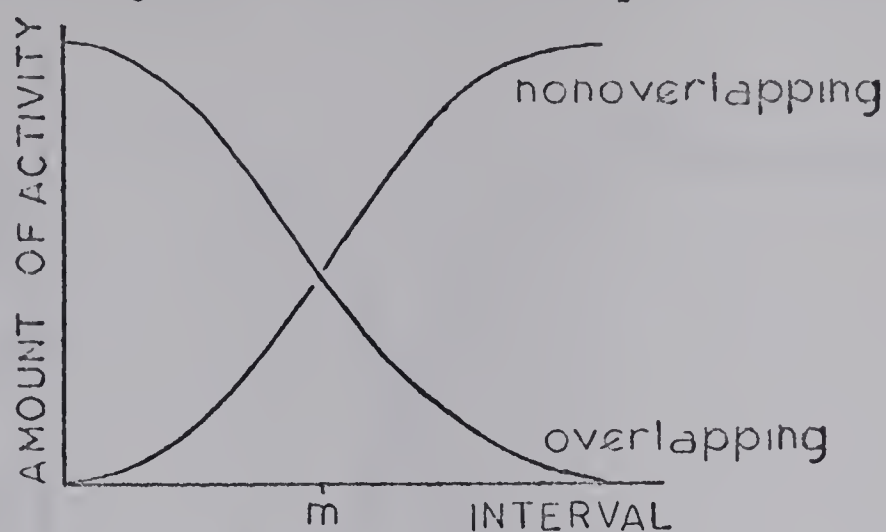


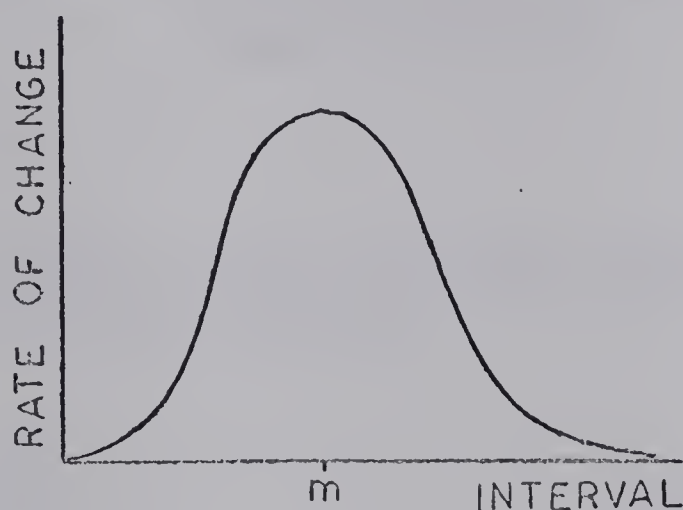
FIGURE 13 The Distribution of Afferent Activity at the Cortex as a Result of Variation in Channel Transmission Rates



A - Amount of overlapping and nonoverlapping activity as a function of pulse interval



B - Rate of change of overlapping and nonoverlapping activity as a function of pulse interval



C - Change in pulse interval necessary to produce some constant change in activity as a function of pulse interval

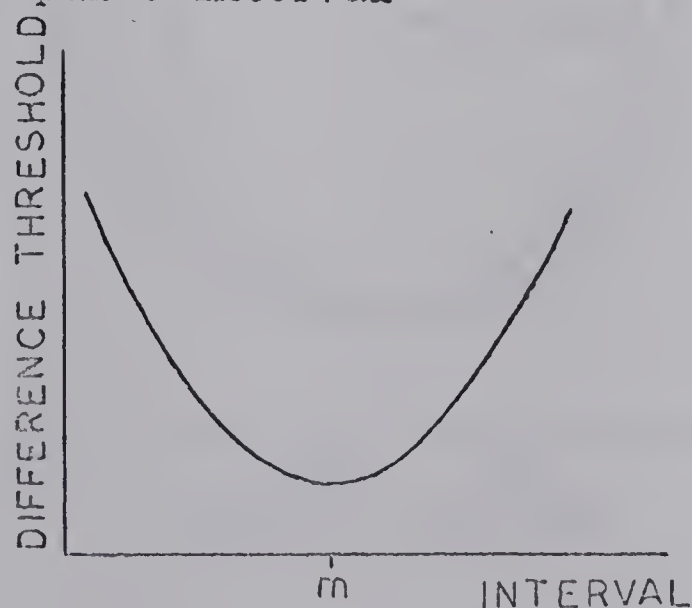
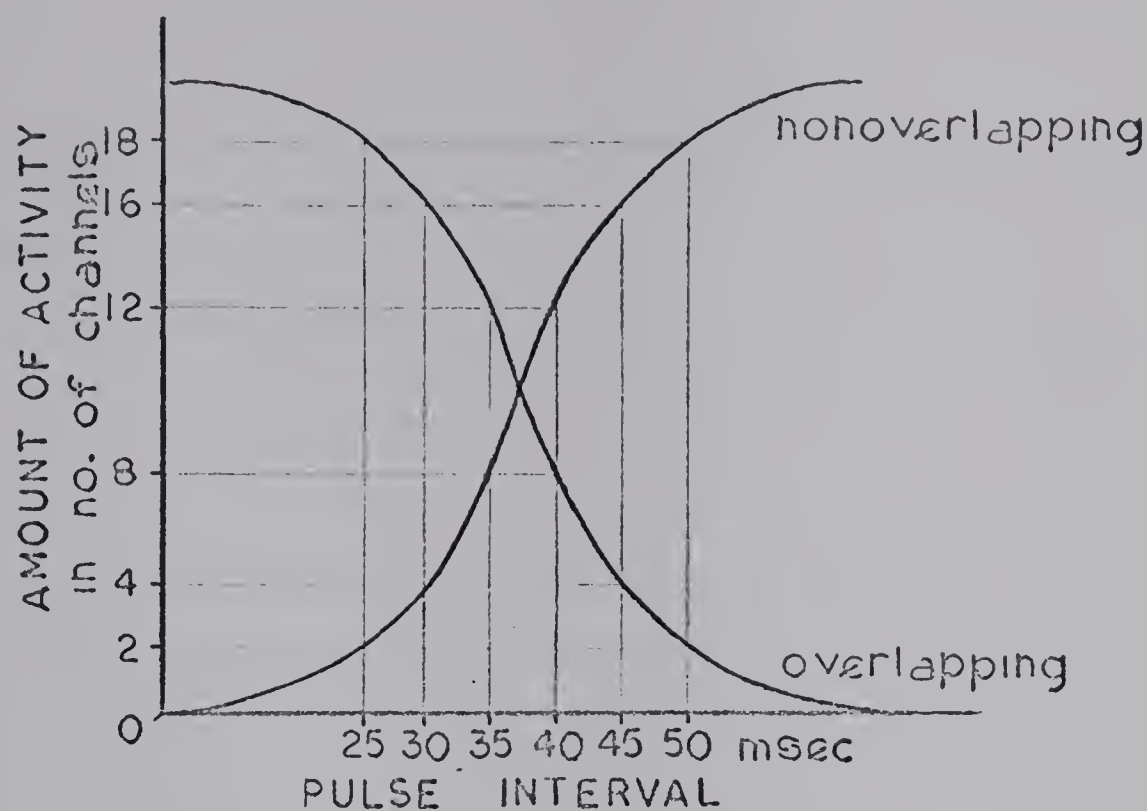


FIGURE 14 How the Amount of Overlapping and Non-overlapping Afferent Activity changes with Pulse Interval and Determines Two-Pulse Difference Thresholds



A - Amount of overlapping and nonoverlapping activity as a function of pulse interval



B - Change in pulse interval necessary to produce some constant change in activity as a function of pulse interval

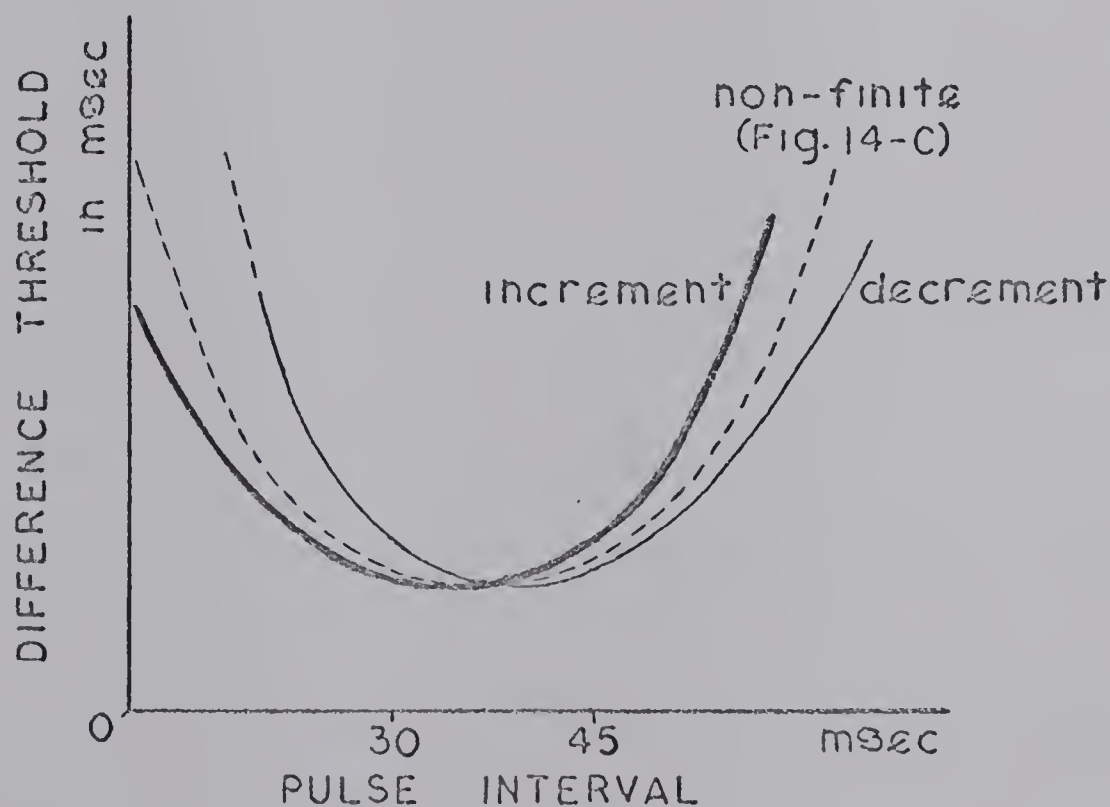


FIGURE 15 Finite Hypothetical Model of how Changes in Overlapping and Nonoverlapping Afferent Activity can Determine Two-Pulse Difference Thresholds





## APPENDICES



## APPENDIX A

## SPECTRAL RESPONSE OF GLOW MODULATORS

Extensive use has been made of glow modulators as a light source for experiments dealing with visual sensory processes. The use of glow modulators for this purpose has been described by Buchmann-Olsen and Rosenfalck (1957), Engel and Howat (1966), Matin (1964), and Riggs (1965). A particular advantage of this light source is its capacity to be accurately turned on and off for brief durations. This capacity is due to the rapid rise and decay times and the stability of the glow modulator's light output.

Matin reports that when irradiated by ultraviolet light to maintain ionization, the lag time of the glow modulator is never greater than 2 usec, while the rise time is about 25 usec. Engel and Howat suggest maintaining ionization by operating the tube at a quiescent current during its "off" state; this method essentially eliminates the gradual increase in light output which otherwise occurs with "on" durations of several seconds. Buchmann-Olsen and Rosenfalck report that the spectral output of the glow modulator is stable over both hours and weeks of use. But they found that light output in the blue and yellow was differentially affected by the rate at which the glow modulator is pulsed. With an increase in pulse frequency, a greater increase in intensity occurred at blue wavelengths. This effect was attributed to an increase in ionization resulting from an increase in the average current. Buchmann-Olsen and Rosenfalck did not, however, use any method to maintain ionization while the tube was in the "off" con-



dition, nor did they report the extent to which this effect occurred. Since glow modulators are often used with rapid pulsing, this study undertook to measure the spectral output of the glow modulator at various currents and at various pulsing conditions.

## PART I: PROCEDURE AND RESULTS<sup>1</sup>

The glow modulators tested were chosen from a group of 36 Sylvania R1131C tubes. This group had been previously tested under standardized conditions for their relative intensity of light output. Tubes of high, medium, and low intensity were selected. The tubes were pulsed by a dual channel timer of high accuracy and driven by a regulated constant voltage power supply. This apparatus was designed and constructed by Biometrics Research. The light output was directed into an O.C. Rudolph monochrometer with a .2mm slit aperture and a 8 mu HIBW. The output from the monochrometer was measured by an 1P21 photomultiplier tube and monitored on an oscilloscope.

### Differences between Tubes

The difference in relative light output of high and low intensity tubes was about that of 50%. The tubes were intermittantly pulsed with 8 msec "on" and 2000 msec "off" times. Figure A-1 shows the spectral response curves for a high and a low intensity tube both operated at 46.5 ma. Though there is considerable difference in the absolute amount of energy at all wavelengths, the relative spectral output

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<sup>1</sup>This work was carried out at Biometrics Research under the direction of Samuel Sutton.





of these two types is similar. The only major difference is the relatively greater height of the peak at 520 mμ in the high intensity tube. In this respect, the response of the low intensity tube appears to be similar to the response of a high intensity tube when the high intensity tube is operated at a considerably lower current.

#### Effects of Current

The spectral output of a medium intensity tube is shown in Figure A-2 at various operating currents ranging from 20 to 40 ma. The tube was intermittently pulsed with 8 msec "on" and 2000 msec "off" times. As current is increased, the total light output is seen to increase fairly linearly at most wavelengths until a current of 35 mA is reached. From 35 to 40 mA the increase is no longer as linear in the region above 500 mμ. The output at wavelengths in the yellow-red region seen to increase less rapidly than the output at wavelengths in the blue-green region. This is particularly evident in the relatively greater increase of the peaks at 490 and 520 mμ compared to the peak at 585 mμ.

#### Effect of Three Hours of Pulsing

The output of a medium intensity tube was tested at the onset and after three hours of continuous pulsing at 8 msec on and 2000 msec off times. The results are shown in Figure A-3. The average increase in light output across all wavelengths was less than 5%. A greater change was observed in the blue than the red region, with a maximal increase of 12% in the peak at 490 mμ. However, it was also noted that the current drawn by the glow modulator had increased from 36 to 37 mA. This indicates that, particularly with a constant current power supply, the change in light output would probably be negligible over several hours of pulsing when the full spectral output is used.



### Effects of Pulsing Rate

A medium intensity tube was tested at various pulsing rates ranging from one pulse every 2000 msec to every 20 msec. The duration of the pulses was 8 msec. The tube was run at 22mA. The results are shown in Figure A-4 for pulsing with 2000, 100, and 20 msec off durations. The average change in light output across all wavelengths was less than 10%. A greater change was noted in the green portion of the spectrum than in the blue-violet or yellow-red, with a maximum increase of 26% at 518 mu.

### Effects of Pulse Duration

A medium intensity tube was pulsed every 2000 msec while its pulse duration was varied from 1 to 50 msec. The tube was run at 22 ma. The results are shown in Figure A-5 for pulse durations of 1, 6 and 50 msec. The increase in pulse duration from 1 to 50 msec resulted in a fairly uniform increase in light output at all wavelengths. The magnitude of this increase was roughly 15% except in the yellow-red region where the increase was somewhat less.

## PART I: DISCUSSION

The effects of varying pulsing rate and pulse duration indicate that the light output of the glow modulator is increased at most wavelengths as the average "on" time of its pulsing is increased. This affect is particularly prevalent in the green region of the spectrum. This finding is in accordance with that of Buchmann-Olsen and Rosenfalck (1957) who attributed such an increase in light output to an increase in mean current which resulted in higher ionization within the tube. This raised the question of whether similar increases in light output occur when the glow modulator is





used strictly for two-pulse operation while a high degree of ionization is maintained by an external ultraviolet source.

## PART II: PROCEDURE

The spectral response of a glow modulator was tested during its two-pulse operation. A Sylvania R1131C glow modulator was pulsed for 1 msec durations in a series of paired pulses. The interval between the two pulses was varied from 1 to 100 msec. The paired pulses were repeated after a delay of 1 sec. The glow modulator was irradiated by an ultraviolet light.

The light from the glow modulator was collimated, passed through neutral density and interference filter, and directed into an RCA 931A photomultiplier tube. Interference filters with pass bands centered at 433, 466, 500, 566, 600, and 633  $\mu$  were used. These filters had an average H1BW of roughly 15  $\mu$ . Neutral density filters of 1.5 log were added to prevent overdriving the photomultiplier. The filters were made by Optics Technology, Inc. The photomultiplier was part of an Eldorado Photometer, model PH200. The output of the photomultiplier was monitored on a Techtronics 503 oscilloscope.

## PART II: RESULTS

At all wavelengths tested, varying the interval of the pulse pairs produced no detectable change in the light output of the glow modulator during the first or second pulse. Figure A-6 shows the output of the photomultiplier at the various regions of the spectrum which were tested. The results indicate that the output of the glow modulator is maximum in the region of 533  $\mu$  and drops off in the blue and red regions when averaged over the wavelengths passed by these filters.





## DISCUSSION &amp; CONCLUSION

The results of Part II indicate that the output of the glow modulator does not vary during intermittent two pulse operation when irradiated by ultraviolet light. As long as pulse duration is brief, the spectral response of the first and second pulse are identical even down to the briefest interval. This consistency of output could be due to two effects: 1) the strong ultraviolet radiation maintained ionization at a high level so that changes in ionization could not be produced by the current through the tube. 2) The brief durations of the "on" time of each pulse did not significantly change ionization. In either case the results of these experiments indicate that the glow modulator is a fairly stable light source under a wide variety pulsing conditions. When irradiated by ultraviolet light and pulsed intermittently for "on" durations of a few milliseconds, the light output is very stable.



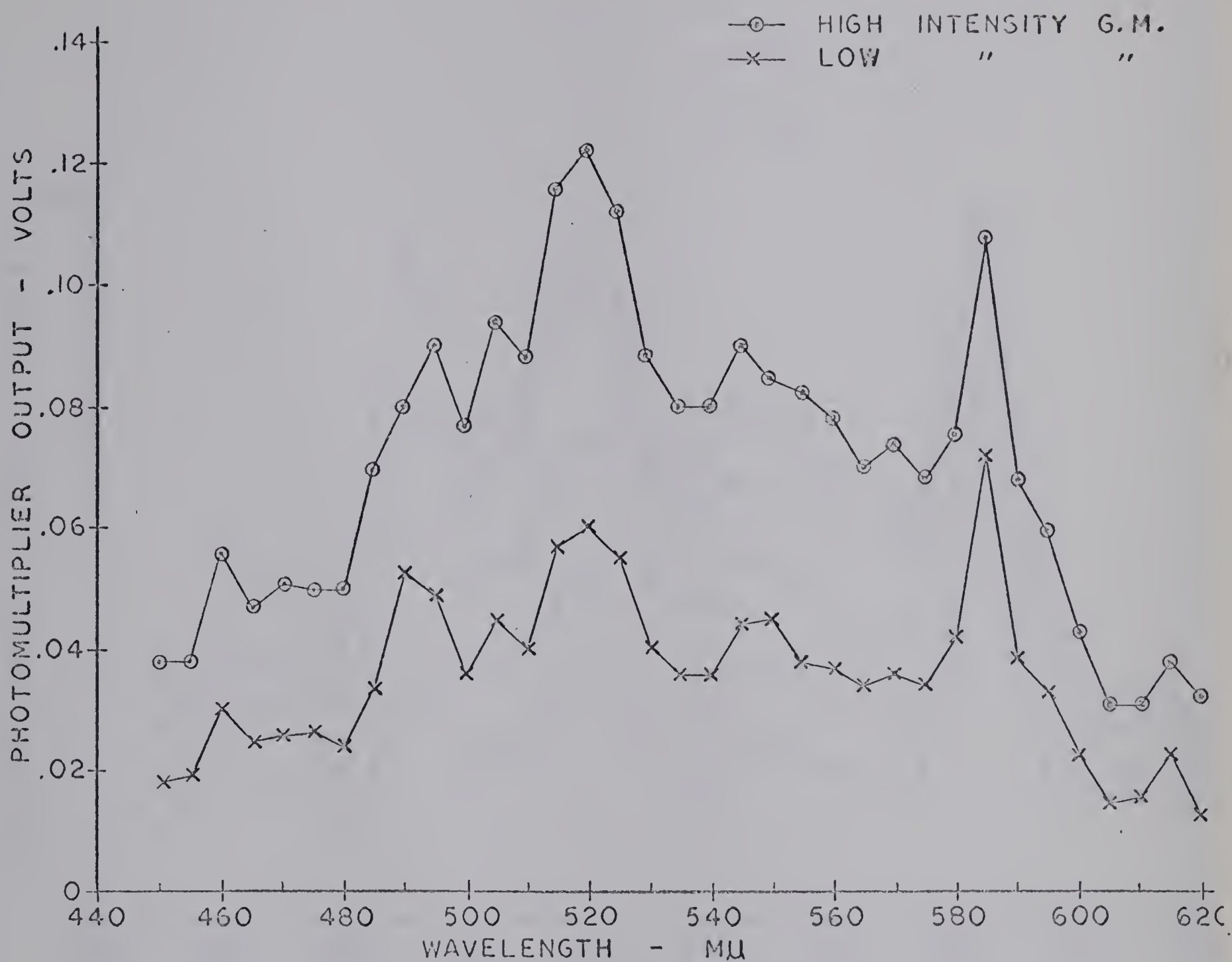


FIGURE A-1 Spectral Output of High and Low Intensity Glow Modulators



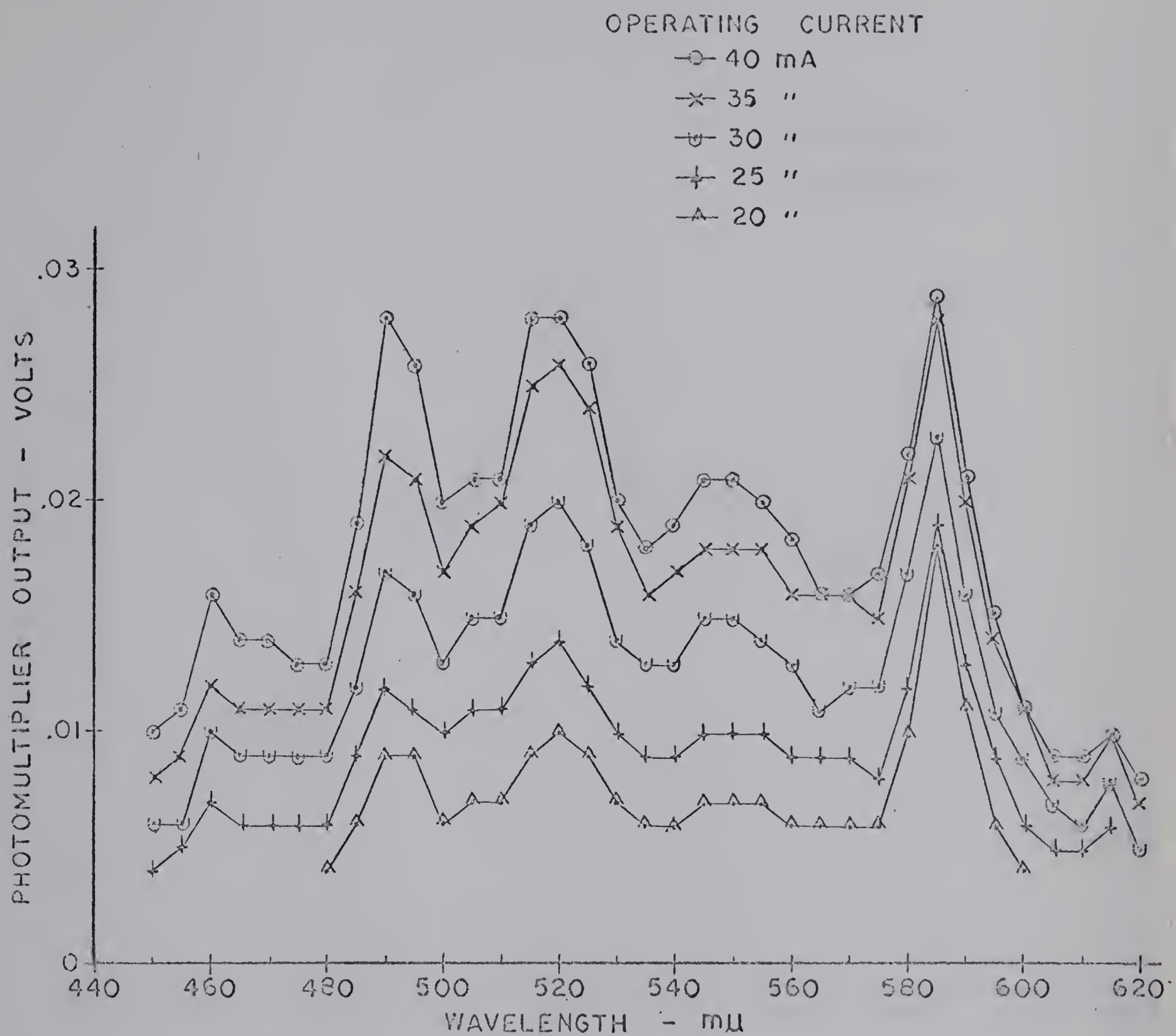


FIGURE A-2 Spectral Output of Medium Intensity Glow Modulator operated at various Currents





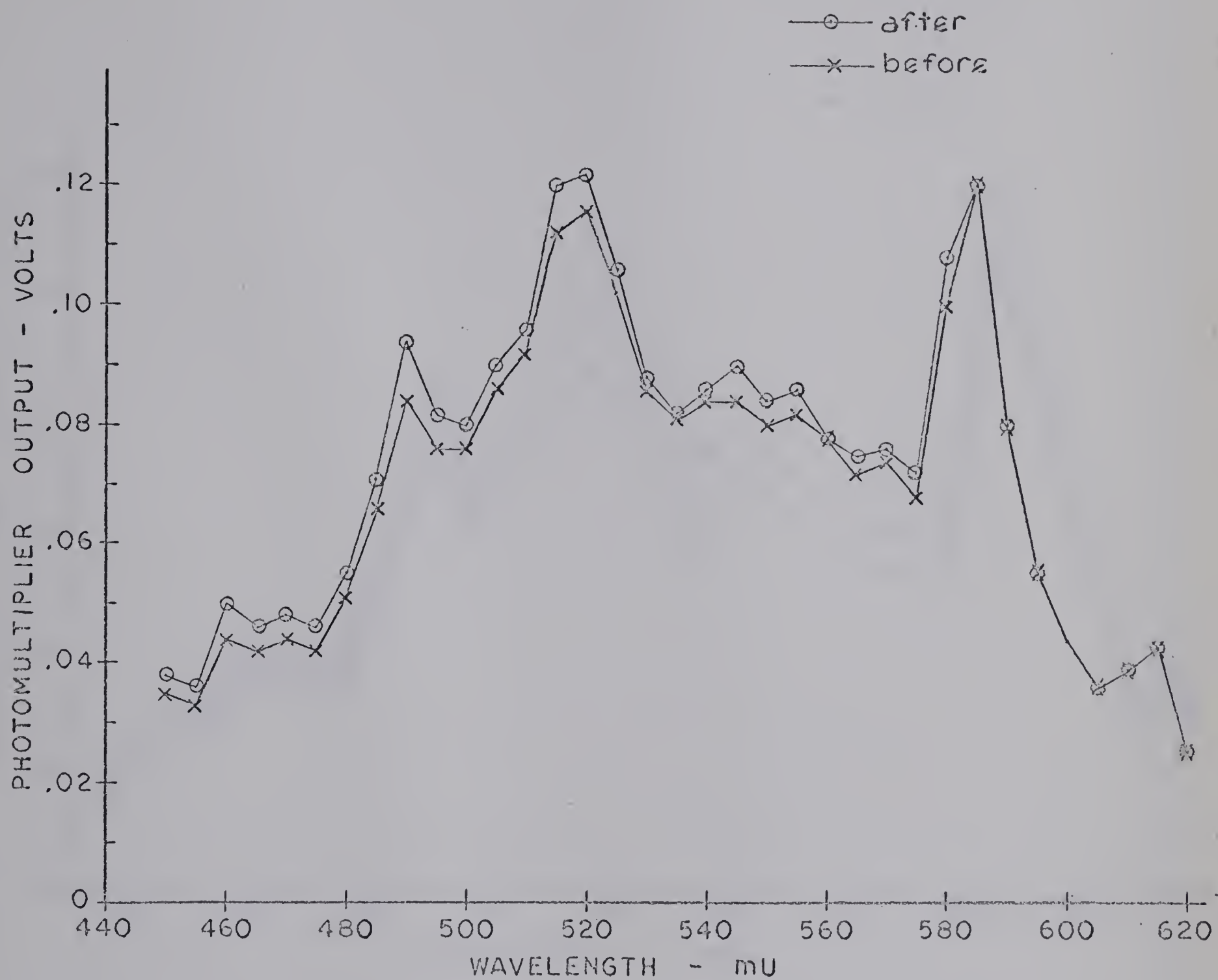


FIGURE A-3 Spectral Output Before and After Three Hours of Pulsing



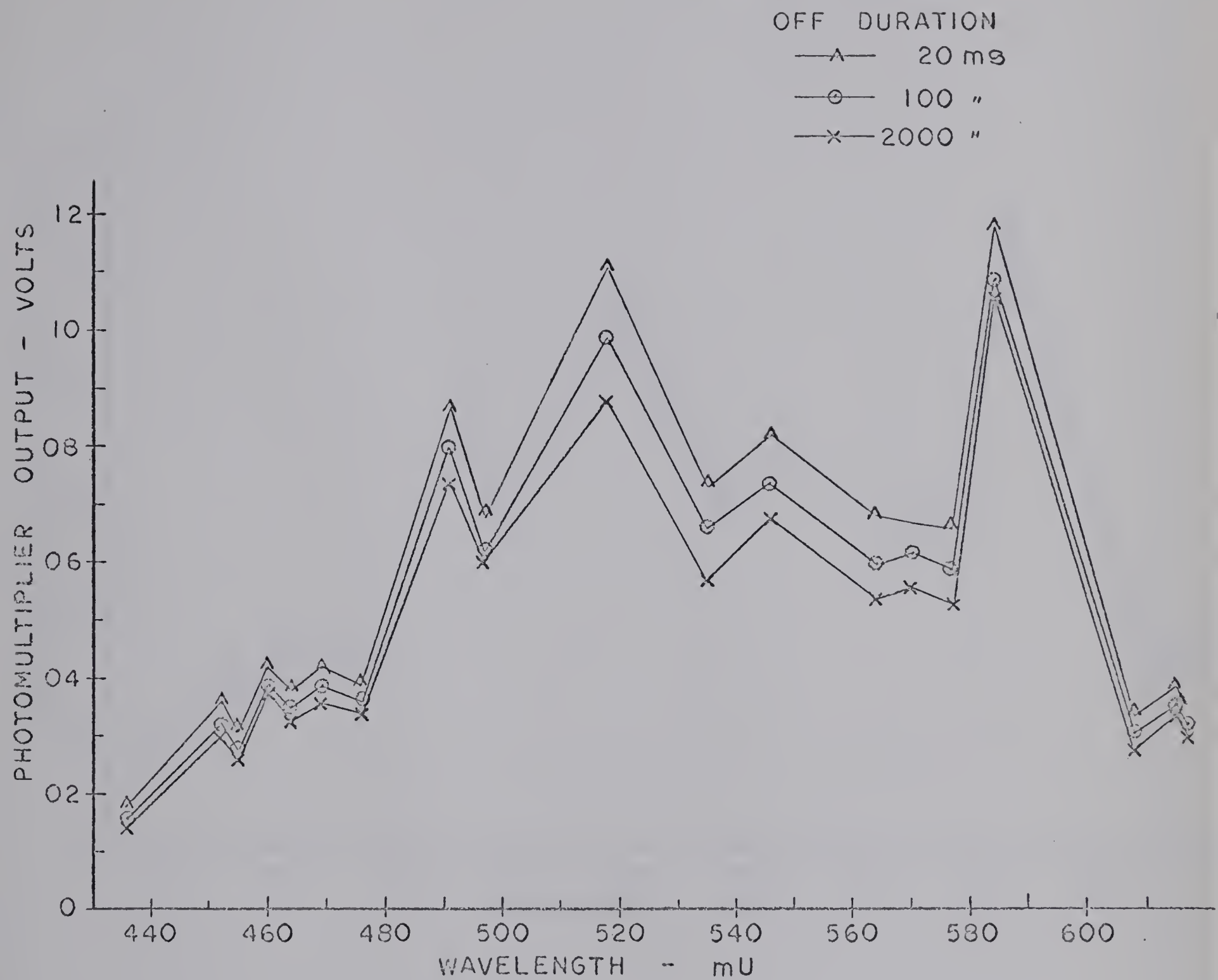


FIGURE A-4 Effects of Pulsing Rate on Spectral Output



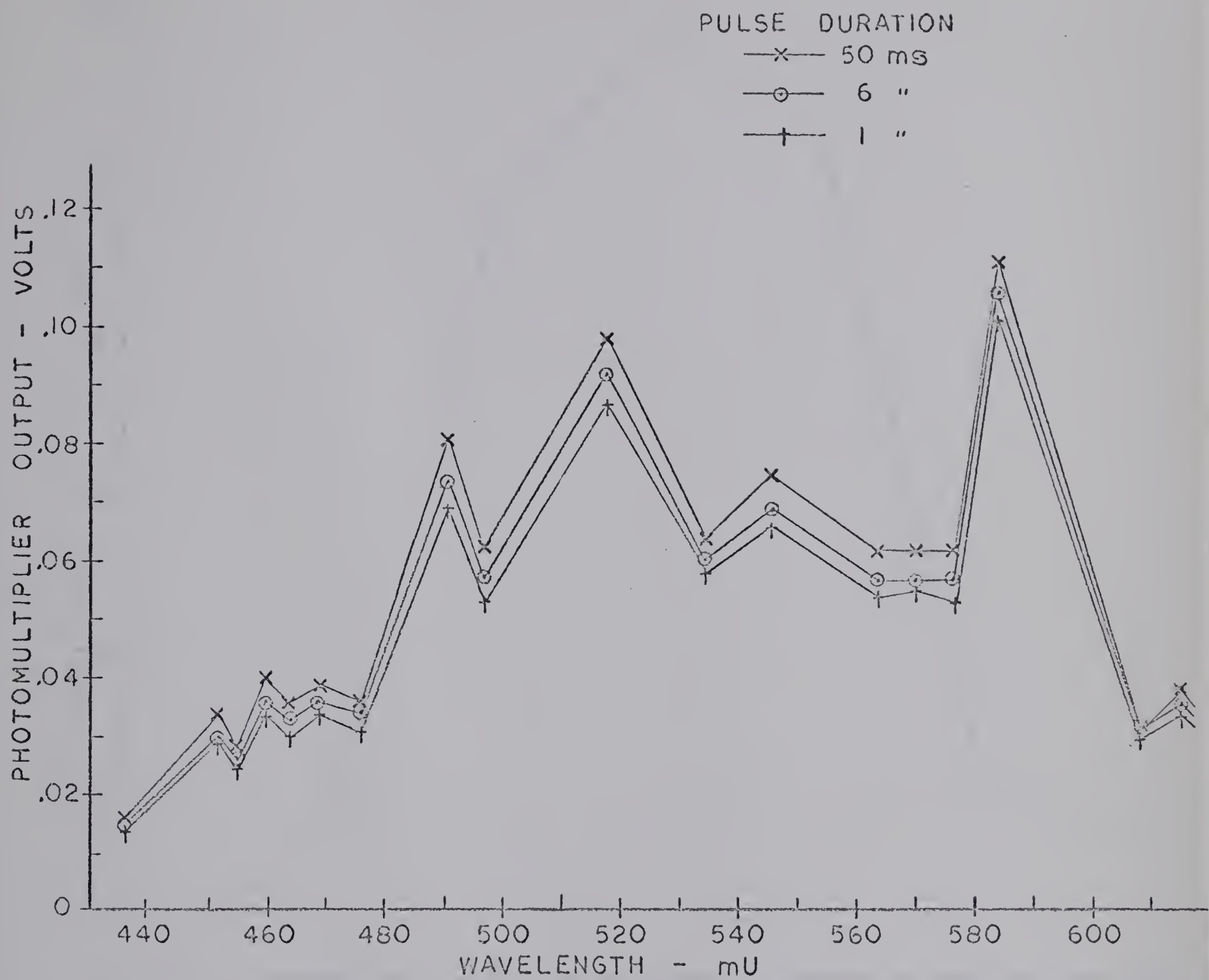


FIGURE A-5 Effects of Pulse Duration on Spectral Output





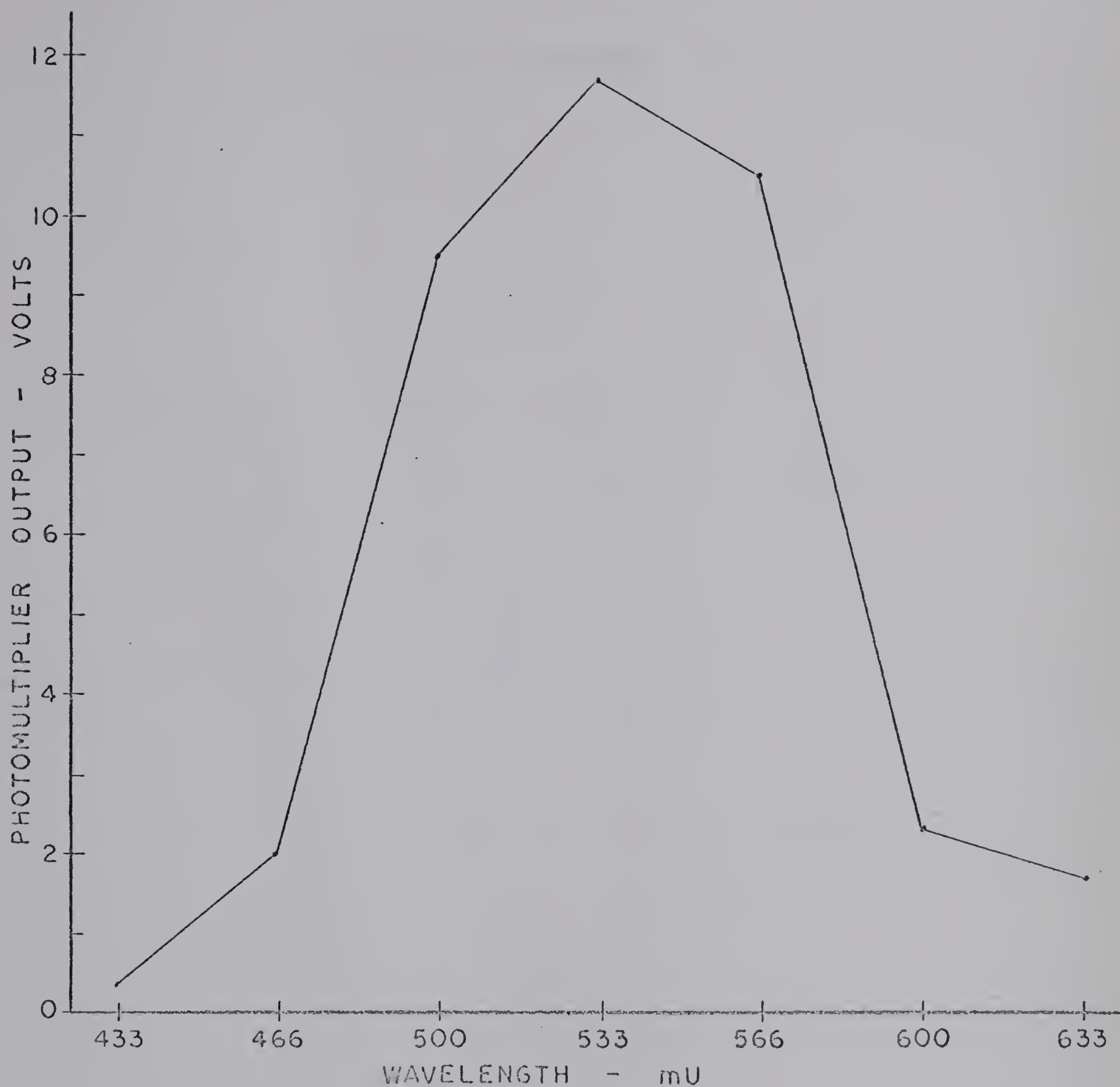


FIGURE A-6 Spectral Output of First and Second Pulses as the Interval between Two Pulses is varied from 1 to 100 msec (The output was identical for both pulses at all intervals.)



## APPENDIX B

## DETAILS OF APPARATUS



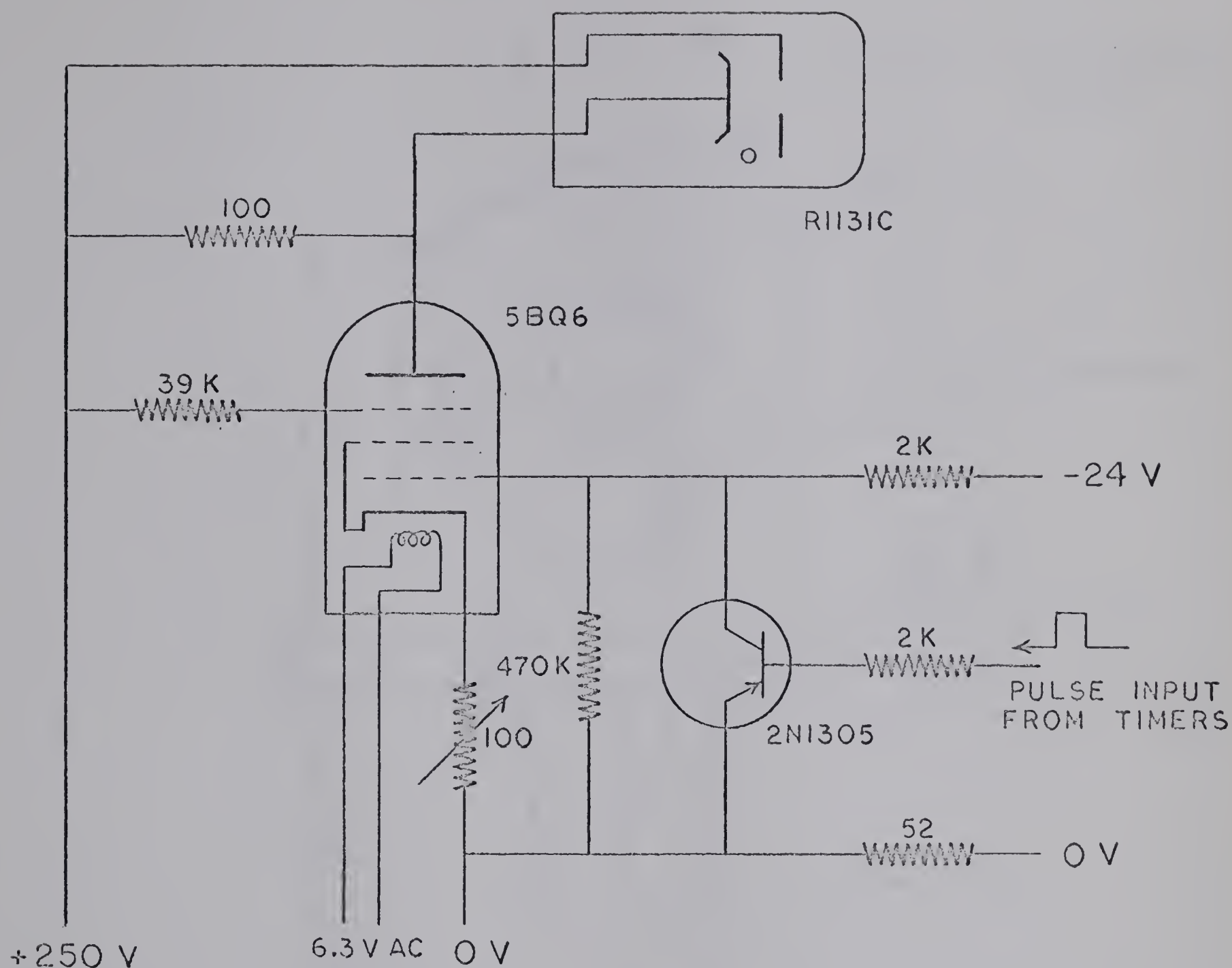


FIGURE B-1 Electronic Gate for Switching Current to the Glow Modulator





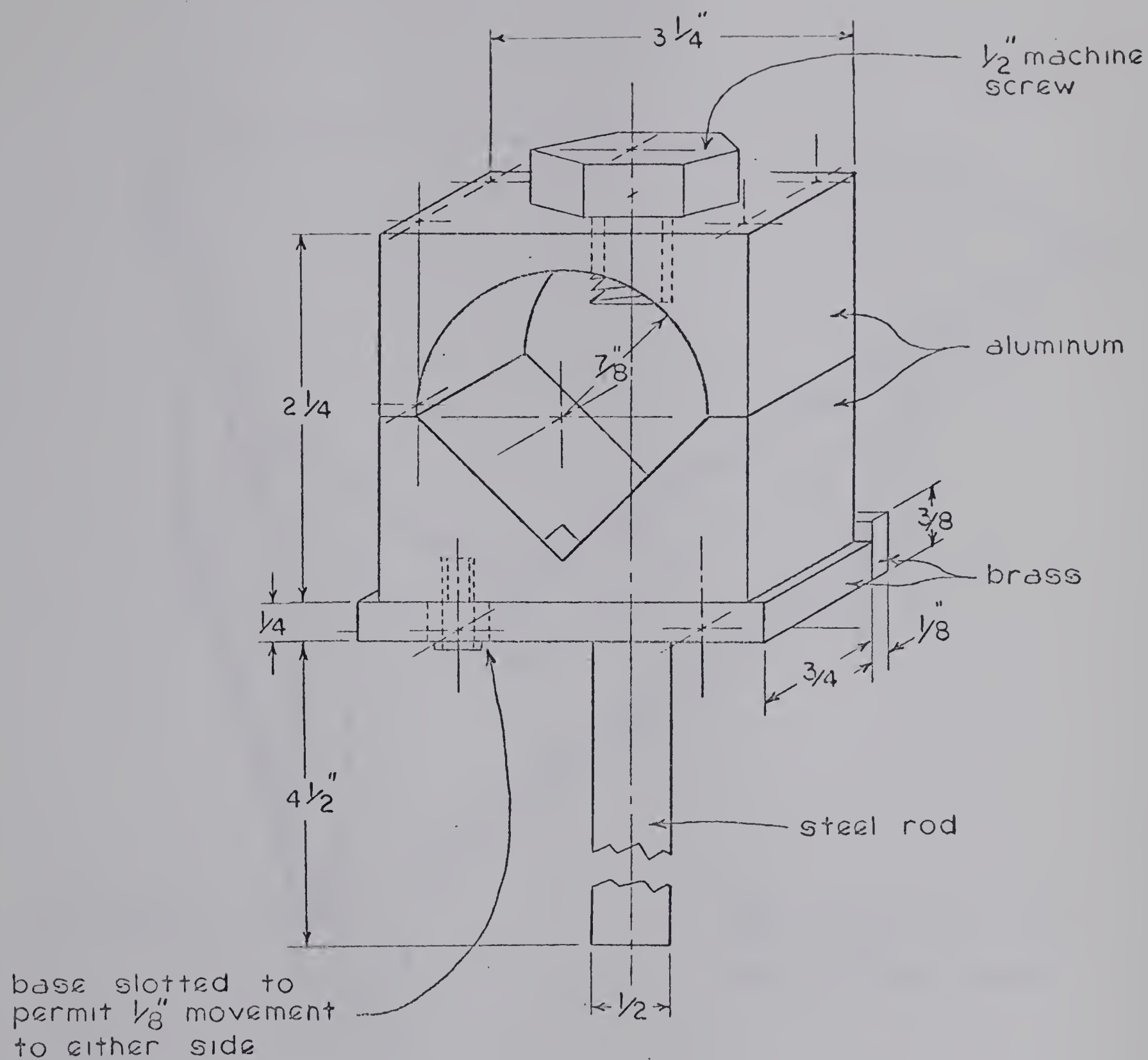


FIGURE B-2 Glow Modulator Holder



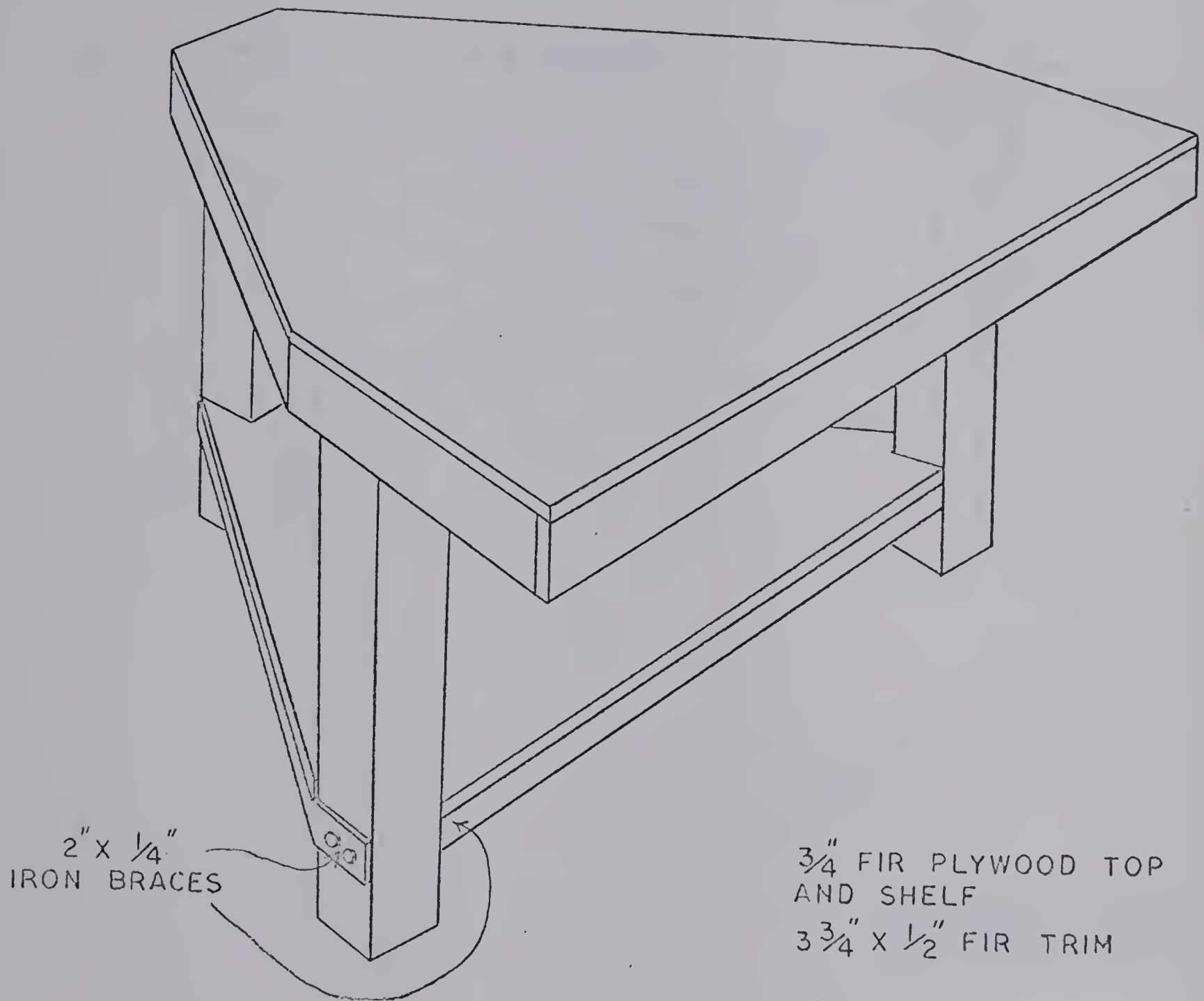


FIGURE B-3 Optical Table - Overall View



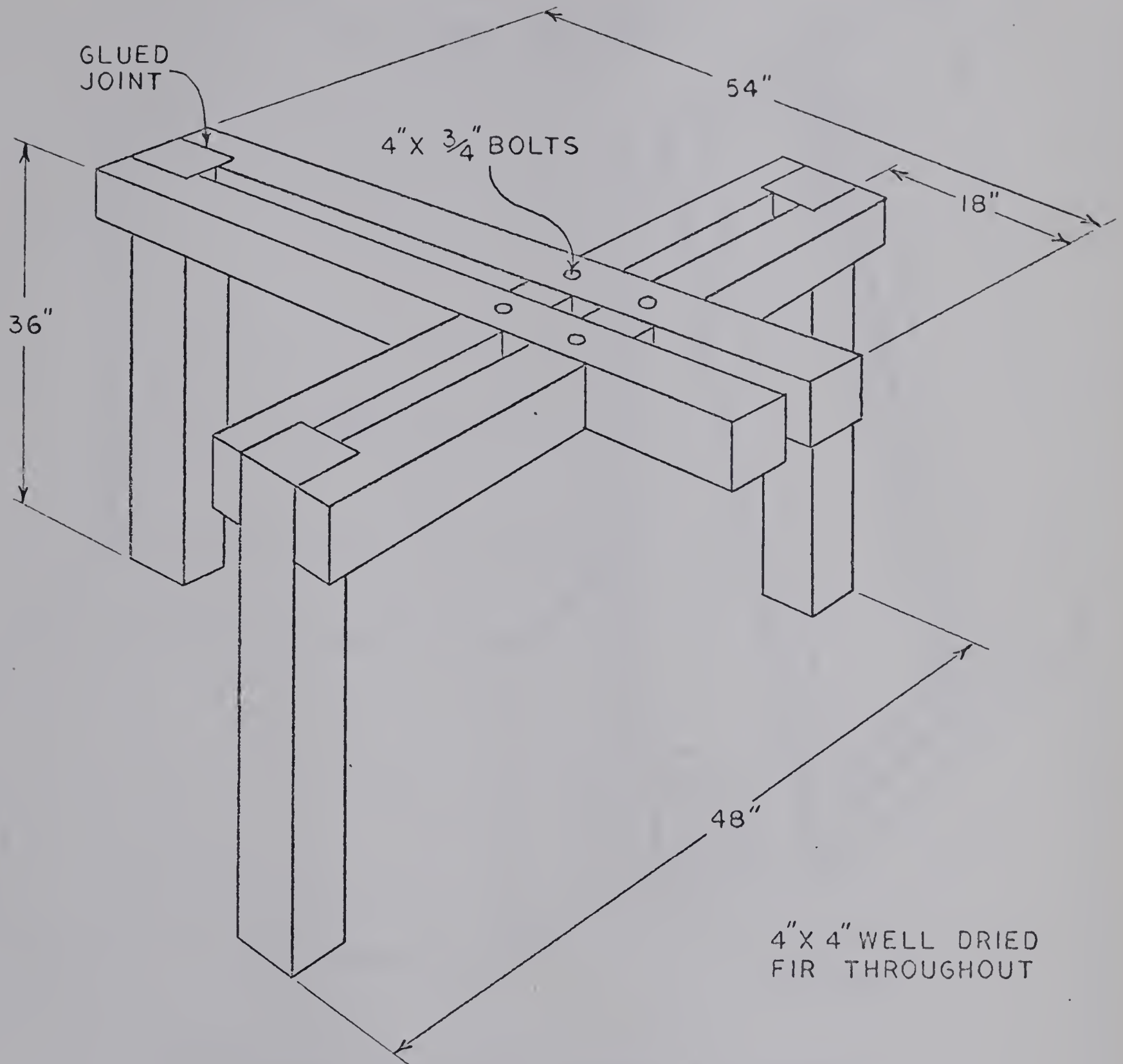
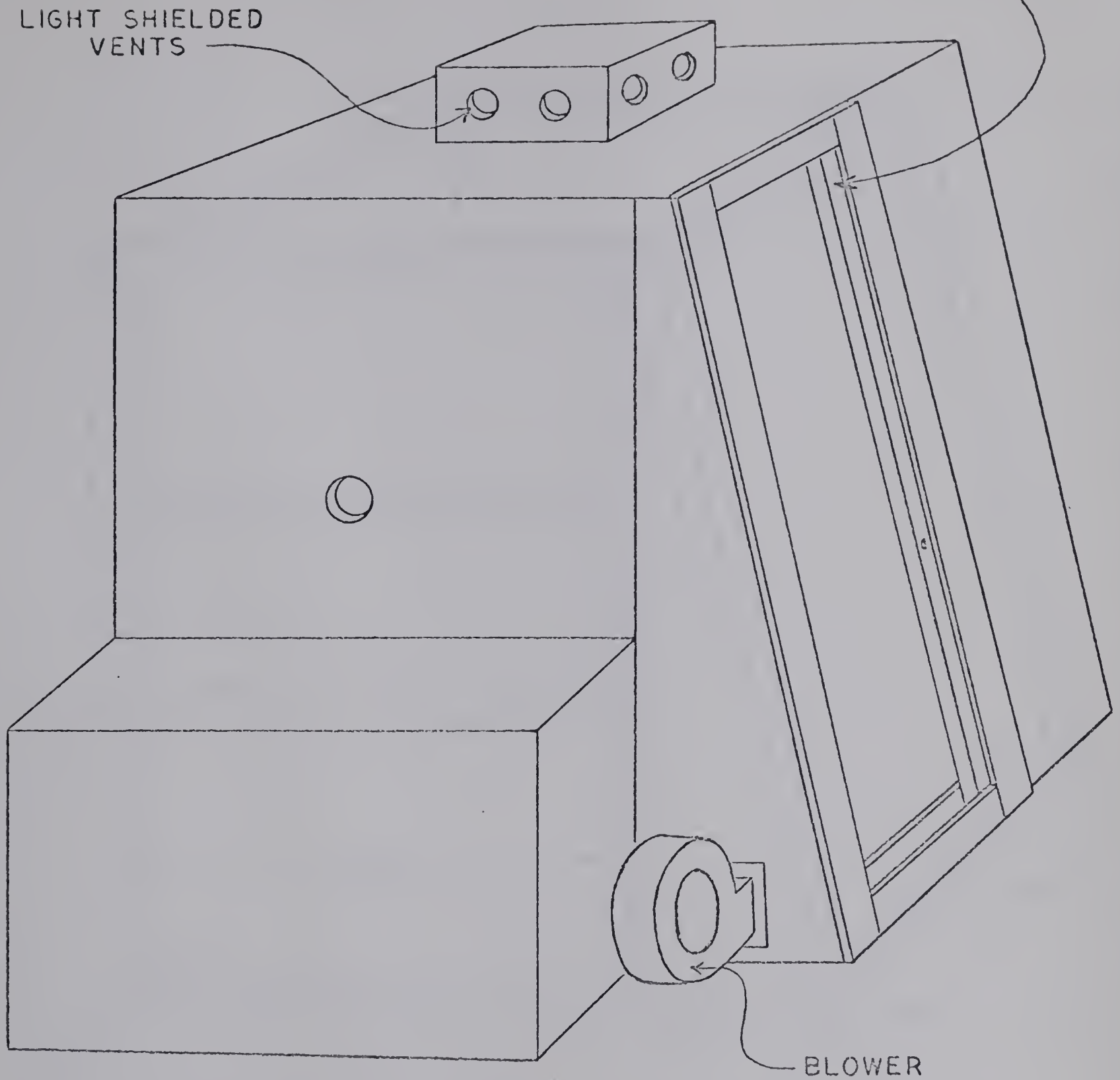


FIGURE B-4 Optical Table - Detail View of Framework



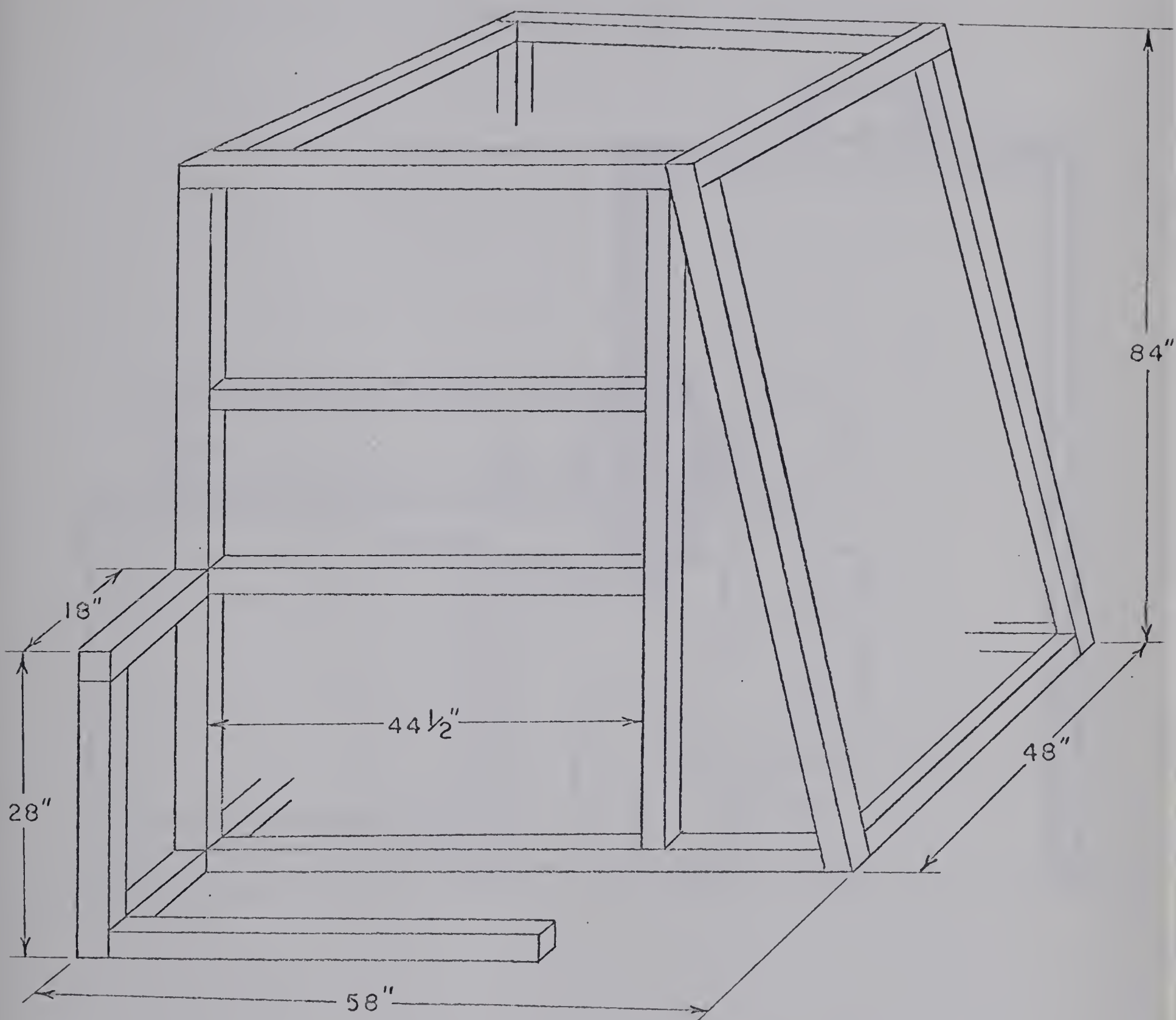




MATERIALS:  $\frac{1}{4}$ " TEMPER BOARD EXTERIOR  
 $\frac{1}{2}$ " FIBER BOARD INTERIOR  
2" X 2" FIR FRAME

FIGURE B-5 Observer Booth - Overall View





2" X 2" WELL DRIED FIR THROUGHOUT

FIGURE B-6 Observer Booth - Detail View of Framework



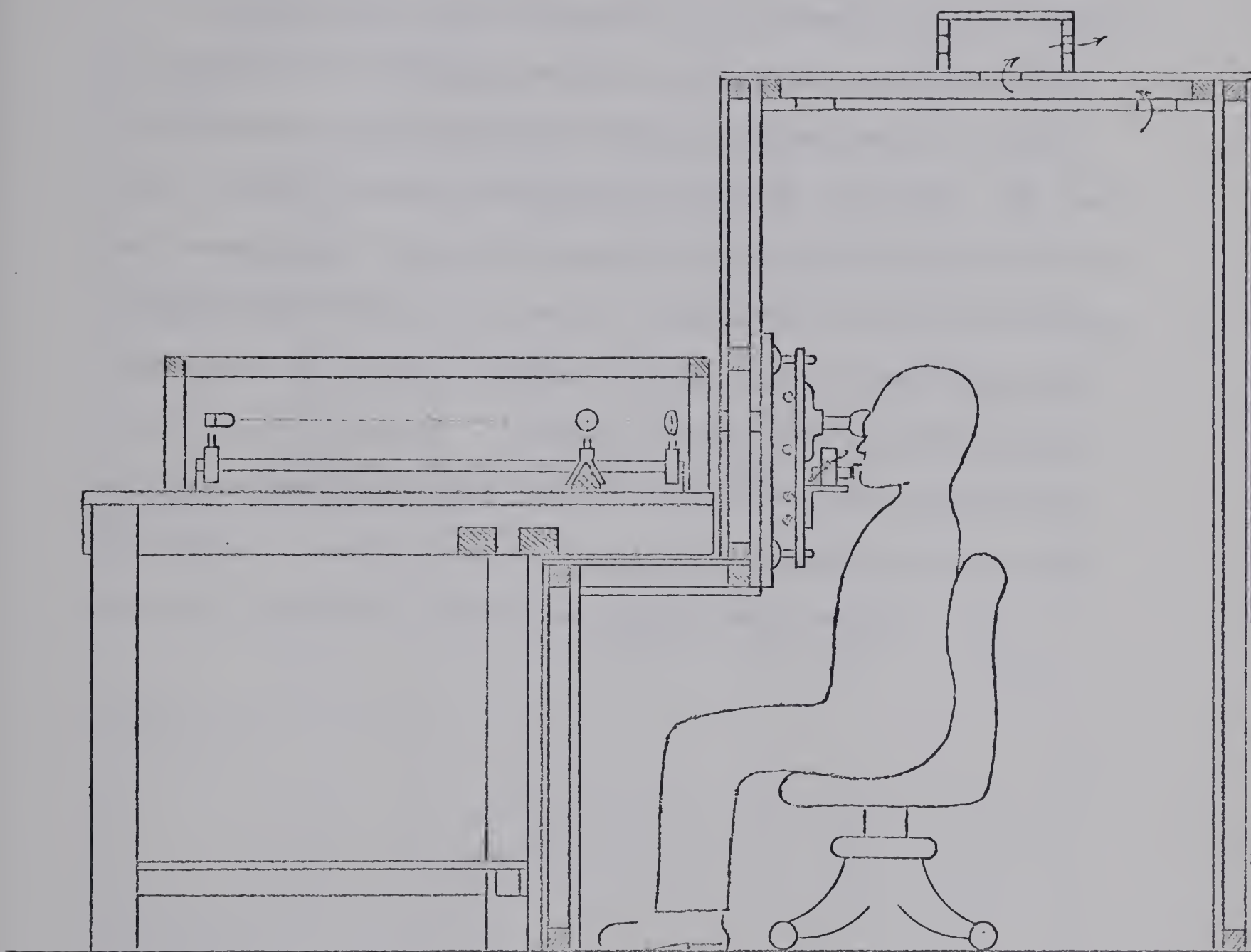


FIGURE B-7    Optical Apparatus and Observer Booth -  
Cross Sectional View





## APPENDIX C

DIFFERENCE THRESHOLDS FOR TWO-PULSE STIMULI WHOSE  
PULSE INTERVALS RANGE FROM 0 TO 60 AND 0 TO 50 MSEC.

These data were collected in an attempt to seek evidence of effects of a scanning process on temporal discrimination. The procedure was identical to that in Experiment I, except that a single stimulus luminance of 200 mL was used. The data are presented in tables C-1 and C-2 for the 0-60 and 0-50 msec ranges respectively in terms of the percent correct discrimination based on 20 observations of each test - comparison condition by each observer. Analysis of the data revealed discrimination functions which did not confirm to the expectations of either a random temporal sensitivity hypothesis or to any scanning hypothesis which the author could devise.



Table C-1: Percent Correct Discrimination At The  
0 - 60 msec Range

Observers:		DD	LE	DH	GL	AW	$\bar{X}$
Comparison Interval							
Test Interval							
0 msec							41.7
12 msec	50%	20	44	60	35		
24	55	40	44	55	50		
36	80	70	70	95	80		
48	100	60	90	95	100		
60	85	80	90	100	85		
12 msec							42
0	45	30	45	35	55		
24	60	45	55	35	25		
36	60	75	35	75	55		
48	65	65	70	90	75		
60	75	85	75	90	75		
24 msec							43
0	30	60	25	70	30		
12	30	45	20	14	35		
36	55	40	35	45	50		
48	75	32	65	70	80		
60	65	65	75	90	60		
36 msec							44.4
0	55	55	35	80	55		
12	50	55	40	75	50		
24	25	45	35	50	35		
48	55	30	40	60	50		
60	60	50	35	85	70		
48 msec							46.6
0	80	85	75	90	75		
12	85	90	30	95	65		
24	70	65	35	90	75		
36	40	45	35	80	30		
60	40	40	25	40	30		
60 msec							43.6
0	100	100	90	100	90		
12	95	90	75	90	90		
24	100	90	65	95	95		
36	80	75	30	95	75		
48	45	45	33	60	35		



Table C-2: Percent Correct Discrimination At The  
0 - 50 msec Range

Observers:						
Comparison Interval		DD	LE	TN	NS	$\bar{X}$
Test Interval						
0 msec						
	10 msec	50%	25	35	60	42.5
	20	30	45	55	60	47.5
	30	40	55	90	65	62.5
	40	60	90	95	85	82.5
	50	85	100	100	95	95
10 msec						
	0	20	20	30	45	29
	20	30	35	55	45	41
	30	60	55	95	70	70
	40	45	75	90	80	72.5
	50	70	85	100	90	86
20 msec						
	0	45	55	55	25	45
	10	40	40	50	35	41
	30	30	40	50	45	54
	40	40	55	80	40	54
	50	65	50	90	95	75
30 msec						
	0	45	50	80	40	54
	10	55	55	90	45	61
	20	55	40	50	25	42.5
	40	25	35	40	25	31
	50	40	50	75	55	55
40 msec						
	0	75	80	100	70	81
	10	55	75	95	60	71
	20	55	70	85	70	70
	30	55	30	55	45	46
	50	15	35	30	40	30
50 msec						
	0	90	90	100	80	90
	10	90	85	100	85	90
	20	90	80	90	70	82.5
	30	70	65	75	70	70
	40	45	50	60	60	54







**B29884**